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A thesis submitted in September 2014 in partial fulfilment of the requirement for the
degree of

Doctor of Philosophy

I hereby declare that this thesis has not been and will not be, submitted in whole or in part to another University for the award of any other degree.

Signature:.....

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Tammy-Ann Sharp

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UNIVERSITY OF SUSSEX

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Exploring the Potential Impact of Carbon, Capture and Storage Technologies on
the Diversity of the UK Electricity System to 2050

SUMMARY

Creating a diverse and flexible energy system to ensure security of supply is at the heart of UK energy policy. However, despite the apparent interest in the idea of securing supply in this way and the term ‘diversity’ becoming more frequently used in this context in government White Papers, policy discourse and the academic literature relatively little attention has been given to exploring what diversity means, how it can be measured, what contribution it can make to different policy objectives and the specific implications for the UK electricity system. Furthermore CCS technologies which are becoming increasingly important to decarbonisation of the power sector in order to meet legally binding greenhouse gas targets set out in the Climate Change Act which raises the question, what are the potential impacts of these technologies on the diversity of the future UK electricity system?

To answer this question a mixed methodology of quantitative energy-economic modelling (using MARKAL), scenario analysis and diversity analysis is combined with qualitative semi-structured stakeholder interviews. Data analysis is carried out in two parts. The first assesses the diversity (with a specific focus on the effect of different input assumptions on CCS technologies) of the scenarios generated using Stirling’s Diversity Heuristic and creates a set of ‘*diversity profiles*’ which map changes in diversity across each scenario. The second part uses stakeholder perspectives to inform the quantification of diversity across the same set of scenarios providing evidence of the impact of different stakeholder perspectives on the overall diversity of the electricity system.

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ABBREVIATIONS

AF	Availability Factor
AGR	Advanced gas-cooled reactor
BERR	Department for Business, Enterprise and Regulatory Reform
CCC	Committee on Climate Change
CCS	Carbon Capture and Storage
CfD	Contract for Difference
CGEM	Computable General Equilibrium Model
CHP	Combined Heat and Pressure
CO ₂	Carbon Dioxide
CPF	Carbon Price Floor
CPL	Contribution to Peak Load
CRTF	CCS Cost Reduction Task Force
DECC	Department of Energy and Climate Change
DTI	Department for Trade and Industry
DUKES	Digest of UK Energy Statistics
EE	Electrical Efficiency
EG	Electricity Generation
EMR	Electricity Market Reform
EPS	Emissions Performance Standard
E-PWR	European Pressurised Water Reactor
ETEM	Energy Technology-Environmental Model
EU ETS	European Union Emissions Trading Standard
FC	Fixed Operation and Management Costs
FF	Fossil Fuels
FGD	Flue Gas Desulphurisation
GDP	Gross Domestic Product
GHG	Green House Gases

GLOCAF	Global Carbon Finance Model
GMM	Global Macroeconomic Model
Gt	Gigaton
GTCC	Gas Turbine Combined Cycle
GW	Gigawatt
IAG	Interdepartmental Analysts Group
IC	Installed Capacity
IEA	International Energy Agency
IEA-ETSAP	International Energy Agency Energy Technology XXXX
IEAGHG	International Energy Association Green House Gas
IGCC	Integrated Gasification Combined Cycle
Int	Intermittent Technologies
IPCC	Intergovernmental Panel on Climate Change
LCOE	Levelised Cost of Electricity
LP	Linear Programming
MARKAL	Market Allocation
MCM	Multi-Criteria Mapping
MDA	Multi-Criteria Diversity Analysis
MEA	Monoethanolamine
MED	MARKAL Elastic Demand
MFP	Ministry of Fuel and Power
MPa	Mega Pascal
Mt	Megaton
MVP	Mean Variance Portfolio
MW	Megawatt
NER	New Entrants Reserve
NERA	National Economic Research Associates
NOx	Nitrous Oxides

Nu	Nuclear Technologies
OEIM	Oxford Energy Industry Model
OPEC	Organisation of the Petroleum Exporting Countries
Oth	Other Technologies
PF	Pulverised Fuel
PIU	Performance and Innovation Unit
PL	Plant Lifetime
PV	Photovoltaic
PWR	Pressurised Water Reactor
RCEP	Royal Commissions on Environmental Pollution
Ren	Renewable Technologies
RES	Reference Energy System
RF	Retrofit
RO	Renewables Obligation
SCR	Selective Catalytic Reduction
SO _x	Sulphur Oxides
SSE	Scottish and Southern Electric
TWh	Terawatt hour
UK	United Kingdom
UN	United Nations
UKERC	UK Energy Research Centre
VC	Variable Operation and Management Costs
WACC	Weighted Average Cost of Capital
WEO	World Energy Outlook

CHAPTER 1. Thesis Introduction

This thesis explores the concept of diversity in relation to the UK electricity system and the deployment of Carbon, Capture and Storage (CCS) technologies. It combines a mixed methodology of quantitative energy-economic modelling, scenario analysis and diversity analysis with qualitative semi-structured interviews with a range of stakeholders to inform the quantification of diversity using a framework of multi-criteria appraisals of different generation technologies.

This introductory chapter briefly introduces the concept of diversity in the context of UK energy policy and highlights the lack of critical attention paid to both the meaning of this concept and its implications, despite the frequent use of the term in UK policy documents. This in combination with an introduction to the role and policy relevance of Carbon, Capture and Storage (CCS) technologies helps to provide the framing for this thesis. The chapter concludes by introducing the research questions and summarising the structure the thesis.

1.1 Introduction

The first UK government department dedicated solely to energy policy was formed in 1974, however, despite the lack of its own department, energy policy had been on the UK agenda since the end of World War II with reference's in the Ministry of Fuel and Power Act 1945 to securing the *'effective and coordinated development of coal, petroleum and other mineral and sources of fuel and power in Great Britain...and of promoting the economy and efficiency in the supply, distribution, use and consumption of fuel and power, whether produced in the UK or not'* Today, essentially the same approach to the energy system, although phrased differently, is still taken and the issue of UK energy remains firmly on the policy agenda with the Department of Energy and Climate Change (DECC) *'working to ensure that the UK has a secure, clean and affordable energy supply'* and suggests that energy security in the UK *'comes from a diverse and flexible energy system...in order to supply consumers with competitive*

energy markets which are effectively regulated and have diversity in supply along with a robust infrastructure with which to provide this' (DECC, 2012e).

However, despite the apparent interest in the idea of securing supply by having a diverse energy system and the term 'diversity' becoming more frequently used in this context in government documents including a number of policy White Papers, very little attention has been given to exploring what diversity means, how it can be measured, what contribution it can make to different policy objectives and the specific implications for the UK electricity system.

In the energy systems literature, it is also true that limited attention has been paid to the theoretical definition and empirical measurement of diversity, both in general and in the specific context of energy systems. However, ideas about diversity have been developed within many natural and social science disciplines, including the business and management literature and mainstream economics. Interestingly, despite the development of different ideas between disciplines, diversity is characterized as '*the nature of degree of apportionment of a quantity to a set of well-defined categories*' (Leonard, 1989). Stirling has developed this definition of diversity further by distinguishing between three mutually distinct properties of diversity, namely:

- **variety** which in this context refers to the number of energy options available in a system,
- **balance** which refers to the proportional contribution of each energy option to the energy system; and
- **disparity** which refers to how different technologies in the system are from one another.

Stirling argues that each of these properties are '*both necessary and fundamental in the constitution of the other two properties but alone proves insufficient*' (Stirling, 1998).

Much of the literature about diversity has neglected the third property, *disparity*, in part because of the difficulties of quantification. This has resulted in the development of quantitative indices of diversity, such as the Shannon-Wiener and Herfindahl-

Hirschman indices, that neglect disparity altogether. Neglecting a property suggested to be fundamental in the constitution of the other two properties results in the portrayal of an incomplete picture of diversity. This thesis will explore disparity in more detail due to its importance in distinguishing between technologies in the electricity generating system which have different attributes and build on subsequent works by Stirling (1994a, 1998, 2007, 2008, 2010) which have focused upon characterising disparity using a process that enables quantification and the development of a heuristic¹ for diversity.

The first practical application of this heuristic was made to energy systems by Stirling and Yoshizawa (2009) and focused upon the diversity of the electricity supply mixes in Japan and the UK. Diversity in these two systems is of particular interest because both governments have sought to promote diversity as a means to improve energy security. This study explored this by conducting a series of in depth interviews with leading stakeholders in energy diversity debates in both countries. The aim of each interview, using a diversity analysis developed based on the aforementioned heuristic, was to elicit detailed information characterising the expert perspective on the performance and other distinguishing attributes of different electricity generating technologies. Thus enabling such perspectives to be incorporated into the quantification of disparity and different viewpoints on the system-interactions between technologies and diversity to be compared and subsequently enabling individuals perspectives on potential trade-offs between portfolio diversity and overall performance to be easily identified. This was visualised by using the data generated to produce a 'map' for each participant of their 'diversity-optimal' portfolio of technologies which was then compared across participants and between countries. The aim of this exercise was to characterise the divergent stakeholder perspectives on the performance and distinguishing attributes of a range of electricity generating options.

This thesis builds on this study and uses a similar set of techniques to explore the diversity of the UK electricity system over the period to 2050. More specifically, it seeks to examine the impact of Carbon, Capture and Storage technologies;

¹ A 'heuristic is a science of problem solving behavior that focuses on plausible, provisional, useful but fallible mental operations for discovering solutions' M ROMANYCIA, F. P. 1985. What is a heuristic? *Computer Intelligence*, 1.

technologies suggested by the UK government to be important in contributing to reducing UK carbon emissions as well as playing an important role the diversity of the UK electricity supply; the latter, a topic not explored in the literature to date.

CCS technologies are currently under development and not yet commercially proven. However, a series of influential studies by bodies such as the IPCC (2005), the IEA (2008a), the WEO (2011) and the UK government (Stern, 2006), have concluded that CCS technologies can provide an essential contribution to reducing global greenhouse gas (GHG) emissions and avoiding dangerous climate change. It is now widely accepted that anthropogenic emissions are a major contributor to climate change and that the restriction of such emissions is necessary to avoid exceeding global temperature rises of 2°C and minimise the impact on ecosystem services and human welfare (IPCC, 2007). In the global context, studies by the IEA and published in the World Energy Outlook (2011) suggest that a 50-60% reduction in global GHG emissions by 2050 (based on 1990 levels) is needed to restrict global temperature rise to just 2°C and that CCS technologies could contribute to approximately one fifth of this reduction. The percentage reduction in developed country emissions will need to be larger, in order to accommodate the growth in emissions from developing countries.

In the UK context, a legally binding target to reduce GHG emissions by 80% (based on 1990 levels) by 2050 was established in the Climate Change Act 2008. The power sector is the UK's biggest contributor to emissions (accounting for 27% of all UK emissions) and modelling studies commissioned by the UK government suggest that up to 70GW of low carbon generating capacity will be required in 2030 with CCS contributing up to 10GW by 2030 and 40GW by 2050 (DECC, 2011a). This compares to total generating capacity of 82GW at the end of 2012, of which only 8.5GW was low carbon (i.e. 4.1GW hydro, 3.2GW wind and 1.1GW other renewable) (DUKES, 2013).

To explore the potential impacts of the deployment of CCS technologies on the diversity of the UK electricity system this thesis will take the following approach. Firstly, an economic-energy model (the MARKet ALlocation model (MARKAL)) of the UK energy system will be used to generate a set of scenarios to explore the development of UK electricity generation in the period to 2050. Secondly, the sensitivity of these

scenarios to different input assumptions will be examined, especially in relation to CCS costs. Third, the diversity of these scenarios will be quantified using a set of baseline assumptions about the disparity of different generating technologies. Fourth, the perspectives of different stakeholders engaged in the CCS debate will be employed to create different categorisations of technology disparity. Fifth, the implications of these different categorisations on the diversity of the generated scenarios will be explored. Finally, the allocations for UK energy and climate policy will be examined.

1.2 Research Questions

Given this context, the primary research question for this dissertation is:

‘What impact could the deployment of Carbon, Capture and Storage technologies have on the diversity of the future UK electricity generation?’

To answer this research question, this thesis uses MARKAL as a tool with which to explore the theoretical concept of diversity using an empirical analysis and in so doing, contribute to the modelling literature, the diversity literature and the UK energy policy literature.

In the context of the UK energy system and recognising the fact that CCS is not yet commercially viable, it seems reasonable to break down this question into three more manageable questions.

1. *What are the potential effects of the deployment of Carbon, Capture and Storage technologies on the diversity of the UK electricity system between now and 2050?*
2. *How are key variables and constraints likely to influence the deployment of CCS and what impact could these have on the diversity of the UK electricity system?*
3. *How does the relative emphasis actors place on the various aspects of technology performance affect their appraisal of electricity system diversity in different scenarios?*

The first research question will be addressed by generating two reference scenarios, one under which the system is able to deploy CCS technologies and one under which the system is unable to deploy CCS technologies. Each scenario will then be subject to a diversity analysis and the profiles of the two compared to determine the effect that CCS has on the diversity profile of the UK electricity system.

The second of these research questions will be addressed by selecting a range of input assumptions and then generating a set of scenarios by varying those assumptions. For each scenario generated a diversity analysis will be completed and a diversity profile generated for each scenario which can subsequently be analysed and compared with the reference scenario as well as the other scenarios generated. This will enable an assessment to be made and subsequently conclusions to be drawn on how certain variables affect the deployment of CCS technologies and how these variables impact on the diversity of the UK electricity system.

The final research question will be addressed by conducting a set of interviews with stakeholders currently engaged in the CCS debate. Interviewees will be required to appraise the technology performance data held within the MARKAL model. The aim of this exercise will be to use the 'appraised data' to generate 'individualised' disparity matrices which can then be applied to each of the scenarios generated to see firstly, if and secondly how, the diversity profile of a scenario changes according to different stakeholder perspectives.

1.3 Thesis Overview

Chapter 2: Contextual Outline: UK Electricity System and Carbon, Capture and Storage Technologies

This chapter provides a contextual outline for this thesis. It begins by providing an overview of CCS technologies, including each of the options for the capture process, transport and storage possibilities. This is followed by a discussion of the context for considering CCS technologies in the UK with a focus on UK climate obligations and the chapter concludes with further discussion of the current status of CCS technologies in the UK to date.

Chapter 3: Energy Systems Diversity

This chapter introduces the concept of diversity and explores its multi-disciplinary origins. It discusses the various indices used to quantify diversity across disciplines and explore their limitations. The chapter then introduces Stirling's Diversity Heuristic and how it seeks to address the limitations experienced with the other indices in quantifying diversity. This chapter goes on to explore the role of diversity in the economy and the energy system and the relevance of diversity to energy policy.

Chapter 4: Energy Systems Modelling

This chapter begins by introducing energy systems modelling and the model used in this thesis, MARKAL. The origins and approach of MARKAL are summarised, along with the mechanisms for scenario generation and the strengths and weaknesses of this approach. The second part of this chapter discusses how MARKAL has been used to inform UK energy policy as well as exploring its limitations in that regard.

Chapter 5: Research Design and Methodologies

This chapter sets out the research questions for this thesis and the gaps in the literature that they seek to address. It explains the research design; the rationale for choosing this approach and justifies the choice of methodologies as well as reflecting on the limitations of these methodologies. This chapter also operationalizes the analytical framework to be used in the subsequent empirical analysis (Chapters 6 and 7).

Chapter 6: Empirical Analysis I

Chapter 6 is the first of two empirical chapters. It describes the scenarios generated using MARKAL and discusses the implications of each of the assumptions on the deployment of CCS. These are discussed in the context of electricity generation, installed capacity and diversity. The discussion of diversity is made possible by the generation of a diversity profile using Stirling's heuristic for each scenario.

Chapter 7: Empirical Analysis II

Chapter 7 is the second of two empirical chapters. This chapter analyses the stakeholder interviews conducted and uses these to generate ‘individualized’ disparity matrices of the different generating technologies. It then goes on to examine how these differing perspectives on disparity influence the estimated diversity of each scenario, and explores the implications of this for overall judgements on disparity.

Chapter 8: Discussion

This chapter discusses the results in the context of the research questions and brings together the findings from chapters 6 and 7 and provides a basis for the conclusions drawn in chapter 9.

Chapter 9: Conclusions, Policy Recommendations and Further Work

The final chapter of this thesis provides conclusions to the research questions set out earlier in this thesis and summarizes the contributions made by this thesis to knowledge. In addition, this chapter also provides policy recommendations arising from this thesis and outlines potential avenues for further research.

CHAPTER 2. Contextual Outline

2.1 Chapter Introduction

This chapter provides some context for the focus of this thesis on CCS technologies. It begins by discussing why CCS technologies are being developed and then summarises the technical specifics of the technologies involved. The chapter then goes on to introduce the context for CCS technologies within the global energy system and summarises the current status of CCS technologies within the UK, including the government's plans for taking these technologies forward.

2.2 An Overview of Carbon Capture and Storage

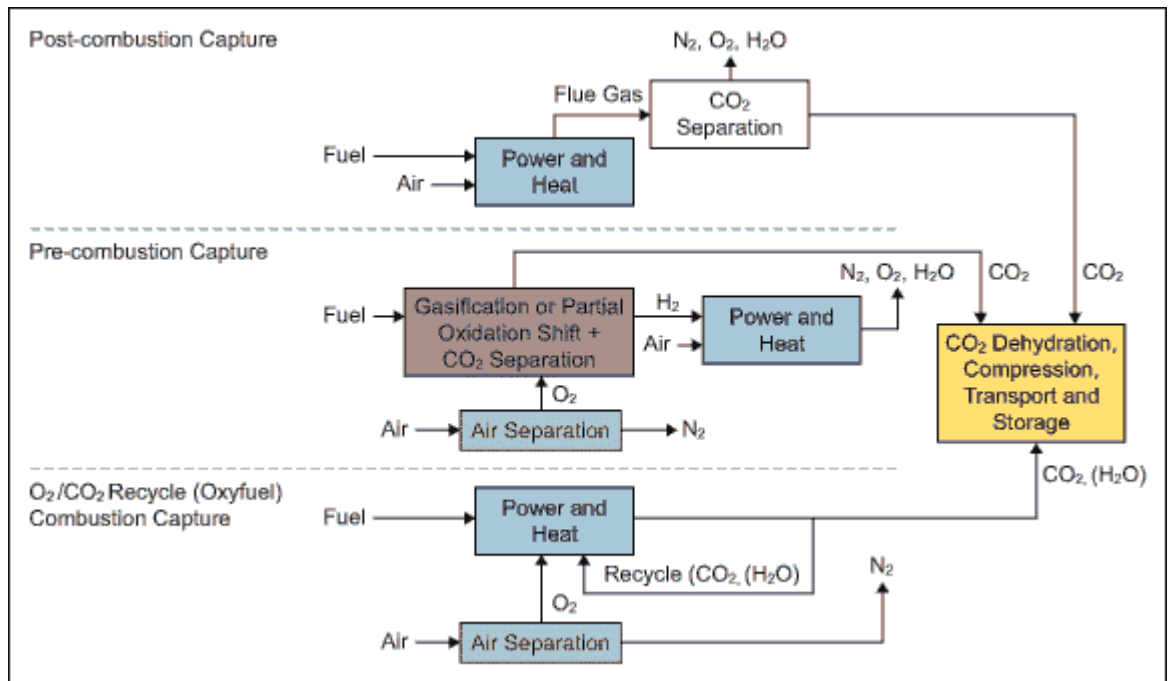
CCS technologies are a set of technologies currently being developed to contribute towards reducing atmospheric emissions of CO₂. The process of CCS uses capture technologies to collect and concentrate CO₂ before transporting it to a suitable storage location where it can be stored safely and permanently away from the atmosphere. If developed at scale, this technology would allow the continued use of fossil fuels with relatively low emissions of greenhouse gases, not only for the power sector but also for other large industrial emitters such as steel and cement factories (DECC, 2009a, IPCC, 2005).

CCS technologies are made up of three component technologies - capture, transport and storage, described briefly below.

2.2.1 Carbon-Capture Technologies

Carbon capture technologies are being developed to capture 85-95% of the CO₂ released during the combustion of fossil fuels or biomass in large-scale plants. There are currently three capture processes being developed with the aim of producing a concentrated stream of gaseous carbon dioxide that can be dehydrated and compressed, ready for transport to storage sites (IPCC, 2005). The three capture processes are post-combustion, pre-combustion and oxy-fuel technology; each of which is undergoing development, testing and deployment at various scales.

Figure 1 - CO₂ capture routes and their chemical processes



Source: (Jordal, 2004)

2.2.1.1 Post-combustion technology

Post-combustion technology separates CO₂ from other flue gases produced during the combustion process. This technology is proven at small scale and most suited to the pulverized coal-fired plants that are currently in operation in many countries around the world. The most modern pulverized coal-fired plants are based on an ultra-supercritical steam cycle with main-steam conditions of 29MPa, 600°C and a reheat temperature of 620°C. An ultra-supercritical steam cycle is the most efficient steam cycle technology available, which uses supercritical² temperatures (>593°C) and pressures, which results in water producing superheated steam without first boiling. The resulting improved thermodynamics (i.e. higher pressure and temperature) of the steam through the turbine means that the supercritical unit is more efficient (i.e. 45-47% in the best case versus 38%) than its predecessor the subcritical unit (DoosanBabcockEnergy, 2009).

² Supercritical means above the 'critical point' for water which refers to the point at which there is no phase change between water and steam (220.89bar).

The post-combustion process involves limestone-gypsum flue gas desulphurization (FGD) and the use of low-NO_x³ burners and selective catalytic reduction (SCR) to minimise the SO_x⁴ and NO_x concentrations in the flue gas. A liquid organic solvent, such as monoethanolamine (MEA), is then exposed to the flue gas, which reacts to remove 85-95% of the CO₂. The reaction between the CO₂ in the flue gas and the MEA produces a CO₂ rich amine⁵, which is then passed through a 'stripper' vessel where the chemical link between the MEA and the CO₂ is broken using low-pressure steam. The released CO₂ can then be processed for transportation and storage (Davison, 2007, IPCC, 2005).

2.2.1.2 Pre-combustion technology

Pre-combustion technology is the most suitable capture technology for coal-based integrated gasification combined cycle (IGCC) plants and for gas-fired combined cycle gas turbine (CCGT) plants. Pre-combustion involves heating the primary fuel in the presence of steam/air or oxygen in a reactor in order to produce a 'synthesis gas', which consists of carbon monoxide and hydrogen. The carbon monoxide is then reacted with steam in a second reactor also known as a 'shift reactor' to produce additional hydrogen and CO₂. The resulting mixture of gases is then separated into a CO₂ gas stream and a hydrogen stream. The CO₂ can then be stored and the hydrogen used as a carbon-free energy carrier that can then be combusted to produce power/heat. The fuel conversion steps are initially more complex and costly than post-combustion capture, but the high concentrations of CO₂ in the shift reactor and the high pressures in this application are more favourable for CO₂ separation (IPCC, 2005).

2.2.1.3 Oxy-fuel technology

Oxy-fuel technology is still at the conceptual stage and is being designed primarily for gas turbines, however integrated pilot plants have been built and plans to build commercial size plants are in the advanced stages of planning. Oxy-fuel technology combusts the primary fuel (natural gas) in nearly pure concentrations of oxygen, which produces a flue gas rich in water vapour and CO₂. A subsequent process of cooling and

³ NO_x refers to nitrous oxides.

⁴ SO_x refers to sulphur oxides.

⁵ An amine is an organic compound derived from ammonia.

compression of the gas stream removes the water vapour leaving a CO₂ stream which is ready for storage when other non-condensed gases such as nitrogen and air pollutants have been removed (IPCC, 2005, IEAGHG, 2007).

2.3 Geological Storage

There are three types of geological storage for CO₂ being considered; oil and gas reservoirs, saline aquifers (sedimentary rocks saturated with formation waters containing high concentrations of dissolved salts) and uneconomically viable coal beds (providing permeability is sufficient). Although methods for injecting CO₂ differ between geological formations it is essentially accomplished by injecting it under pressure into porous rock formations (which have previously held fluids such as natural gas or oil) below the Earth's surface. Suitable rock formations for storage can occur both on and offshore, typically in sedimentary basins (IPCC, 2005).

There are several storage projects on-going at an industrial scale including the Norwegian Sleipner project in the North Sea which utilises an offshore saline aquifer, the In Salah project in Algeria utilising an onshore saline aquifer and the Weyburn project in Canada which uses a system of Enhanced Oil Recovery (EOR). EOR involves injecting CO₂ into an otherwise uneconomical oil well to force oil out of the reservoir into production wells. Many of the technologies used for injection are the same as those that already exist in the oil and gas industry, including well-drilling technology, injection technology, and computer simulation of reservoir dynamics and monitoring methods. These are being further developed for the design and operation of geological storage (IPCC, 2005).

2.4 CO₂ transport

The options for CO₂ transportation include shipping, pipelines and road tankers. In the UK and for large-scale CO₂ transport, pipelines are the most cost-effective option. CO₂ is transported in a super-critical state and at a density ten times higher than that of natural gas (this requires less energy for transport). There is already 6,200km (0.6-0.8m diameter) of CO₂ pipeline in existence around the world, transporting approximately 50 Mt of CO₂ annually. The transport of CO₂ is not without its risks.

When the density of CO₂ is less than that of air then this carries with it the risk of leaks leading to the accumulation of CO₂ at ground level. However, operation records for CO₂ pipelines show low rates of leakage and relatively low risks to safety (ETSAP, 2010).

2.5 Context for considering Carbon Dioxide Capture and Storage in the UK

There is overwhelming scientific consensus that anthropogenic GHG emissions are the primary contributor to climate change that an increase in average global temperatures of more than 2°C above preindustrial levels could have serious environmental, economic and social impacts. The Kyoto Protocol was one of the first steps in recognising the need to reduce global GHG emissions to prevent the serious consequences of climate change and is an international agreement linked to the United Nations Framework Convention on Climate Change, which commits its Parties to emissions reductions by setting internationally binding targets. Overall, this equates to a reduction in global GHG emissions of 20-24 billion tonnes by 2050 (around 50-60% below current global levels). The Protocol recognises that industrialised countries are principally responsible for the current level of GHG emissions and subsequently places a heavier burden on developed nations under the principle 'common but differentiated responsibilities'. The Protocol was adopted in 1997 and entered into force in 2005 with the detailed rules for its implementation adopted at the 7th Conference of the Parties in Marrakesh. The first commitment period ran from 2008-2012 and committed 37 industrialised countries and the European Union to reduced GHG to an average of five percent against 1990 levels. The second commitment period runs from 2013-2020 and commits its Parties⁶ to reduce GHG emissions by at least 18% below 1990 levels (UNFCCC, 1998).

In the UK, Kyoto Protocol targets were set at a 12.5% reduction in GHG emissions in the first commitment period and a 20% reduction in GHG emissions in the second commitment period, based on 1990 levels. Findings by the Committee on Climate Change⁷, the IEA and the European Commission (EC) all suggested that in order to have

⁶ The composition of Parties between the first and second commitment period varies.

⁷ An independent body established under the Climate Change Act to advise the UK government on GHG emissions targets, and to report to Parliament on progress made in reducing GHG emissions

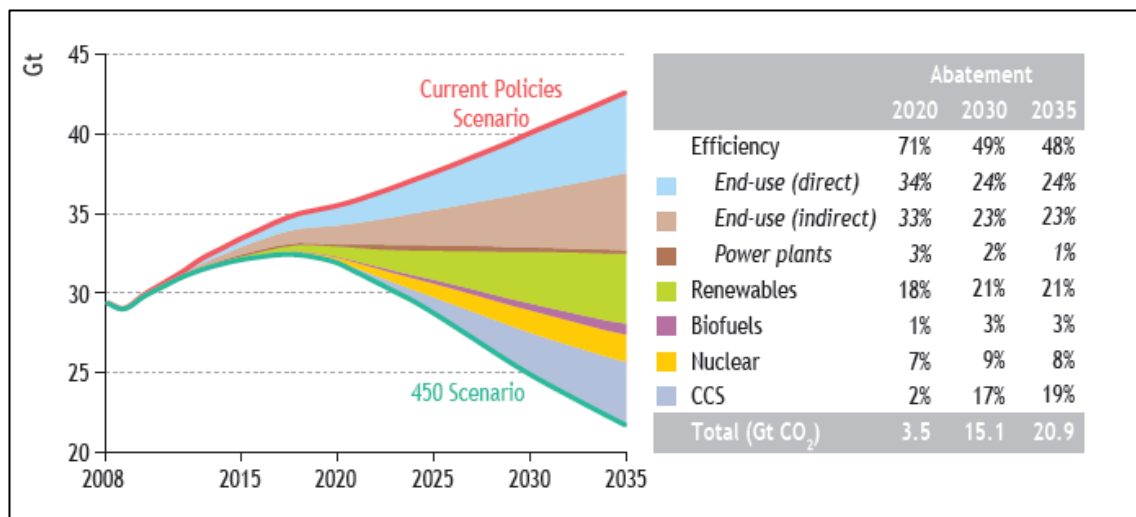
a 50% chance of keeping below a 2°C rise in preindustrial that GHG concentrations must stabilise below 450ppm CO₂ equivalence (which is becoming an increasingly harder target to meet) and that the probability increases to ~66-90% if stabilisation occurs below 400ppm CO₂ equivalence. The UK contribution to this should be a reduction of emissions to 146-180 MtCO₂e by 2050, compared to a 1990 baseline of 797 MtCO₂e (a reduction of 78-82%) (CCC, 2008). The CCC suggest that in order to form part of a fair global climate deal, the UK and other developed countries need to reduce their emissions over the long-term to a per capita level which, if applied across the world would be compatible with the climate objectives described and equates to just over 2 tonnes of CO₂-equivalent per capita with little scope for deviation. Comments by Lord Stern (2008) highlight the fact that developing countries will also need to make substantial cuts but should not be asked to take on binding targets until developed countries can provide the example of lower carbon growth and can demonstrate that institutions and frameworks can provide the necessary financial and technological support this. With this in mind, he also goes on to suggest that it is difficult to identify developing countries that will actually be able to run their economies with emissions below 2.1-2.6 tonnes per capita in 2050. Therefore if there are not major economies with emissions significantly below the global average then there cannot be developing countries significantly above. With this in mind, this has led to the UK setting a legally binding target to reduce its greenhouse gas (GHG) emissions⁸ by at least 80% compared to 1990 levels by 2050 (CCC, 2008); a target recommended by CCC to be in line appropriate global and UK targets in order to contribute to reducing the risk of dangerous climate change and an analysis of the technological feasibility of radical emission cuts and the possible costs of achieving them.

This target was accepted by the government and formed part of the Climate Change Act 2008, which makes it the duty of the Secretary of State to ensure that the UK is on a path consistent with reducing emissions of GHGs to 80% below 1990 levels by 2050 (DECC, 2008).

⁸ Set out in the Kyoto Protocol as carbon dioxide (main component), nitrous oxides, methane, sulphur hexafluoride, hydrofluorocarbons and perfluorocarbons.

Analyses by the Intergovernmental Panel Climate Change IPCC (2005), the International Energy Agency (2008a) and the UK government (2006) amongst others, suggest that CCS technologies will provide an essential contribution to these emission reductions. Both major economies i.e. the US and emerging economies such as China and India are overwhelmingly dependent on fossil fuels (especially coal) and are likely to remain so for decades. Studies by the IEA on behalf of the G8⁹ have suggested that to reduce carbon emissions by 50% by 2050, large-scale deployment of CCS will be required. For example, in the IEA 450 Policy Scenario¹⁰, CCS is anticipated to deliver 15% of total emission reductions (see Figure 2) arising from 187GW of capacity installed globally (127GW of which is Coal CCS and 60GW Gas CCS) (IEA, 2008b).

Figure 2 – World energy-related CO₂ emission savings in the IEA 450 Scenario



Source: (WEO, 2010)

The IEA 450 Policy Scenario suggests that in order to achieve this CCS would need to capture and store 3890 million tonnes of CO₂ (equivalent to 1100 million cubic metres), however, Smil (2011) demonstrates that sequestering just a fifth of current CO₂ (using a compression rate similar to crude oil) emissions from fossil fuel combustion would occupy a massive 8 billion cubic meters¹¹. Thus, with this figure in mind we would need to create a completely new worldwide industry right through

⁹ G8 (Group of Eight) is a forum for governments of the world's largest eight economies (EU, US, UK, Russia, Japan, Italy, Germany, France and Canada) to discuss issues of mutual of global concern.

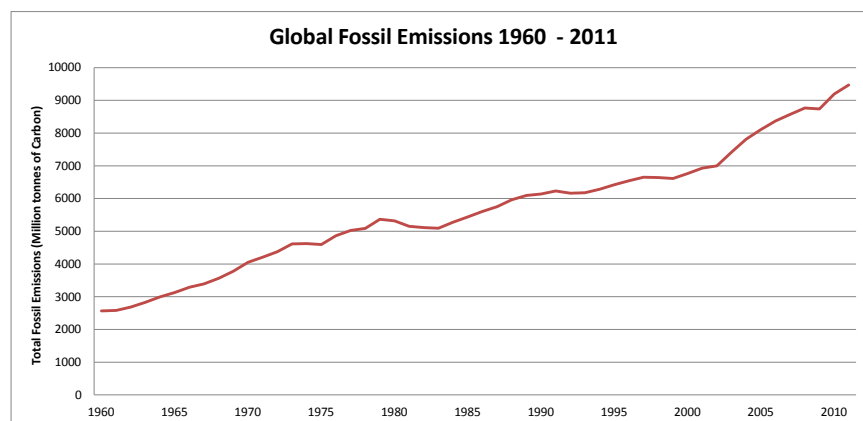
¹⁰ 450 Policy Scenario – an energy pathway that sets out the goal of limiting global temperature rises to 2°C by limiting the concentration of GHG in the atmosphere at 450 parts per million IEA 2008b. World Energy Outlook..

¹¹ Volume calculated by dividing mass by density (3890 million cubic tonnes/800kg/m³)

from the capture process to the storage process whose annual throughput would need to be 70% larger than that of the global oil industry at present with an infrastructure that took several generations to build just to deal with this 20% of emissions. Of course, this is technically possible but not within the time frame that would prevent CO₂ levels from rising above 450ppm. However, the important point to note from this discussion is that whether you agree with the results from the IEA Policy 450 scenario or with Smil's comments, that views on how much CO₂ can be stored and how quickly it can be stored is surrounded by much debate and controversy.

In the absence of CCS the IEA estimates that the cost of maintaining global temperature rises below the 2°C mark will increase by some 70% (IEA, 2009); a figure not considered in light of Smil's calculations discussed above. The latest estimates of global emissions by the IEA suggest that energy-related CO₂ emissions in 2010 were at their highest in history (see Figure 3) (rising 4.6% in 2010, having declined in 2009 due to the global financial crisis), with coal combustion responsible for 43%, oil for 36% and gas for 20% (IEA, 2012). In 2020, it is estimated by the IEA that 80% of emissions will be 'locked-in'. This means that the plants responsible for these emissions will already be in place or under construction; highlighting the need for CCS technologies be developed for application to both new build and existing infrastructure (DECC, 2012b).

Figure 3 – Total Global Fossil Emissions between 1960 and 2011



Source: (Boden et al., 2011)

In the UK, the power sector is the biggest contributor to emissions, accounting for 27% of UK's carbon emissions in 2011 (DECC, 2011d) with around 75% of fuel used in this

sector from fossil fuel. DECC, the CCC and other commentators agree that emissions from the power sector need to be close to zero by 2050.

There are a number of options for decarbonising the UK's power sector and the UK government's stated policy is not to 'pick winners' to achieve this but rather to allow technologies to compete with one another to ensure the target is delivered at least cost (DECC, 2003a). Despite this, it is still possible to generate projections using the best available models and data. The government has commissioned a number of modelling exercises and the one underlying the UK Carbon Plan (discussed in more detail in Chapter 4) suggests that 40-70GW of new low carbon generating capacity will be required by 2030 (subject to demand and the generation mix built), compared to the 10 GW installed in 2011. The Carbon Plan estimates that CCS could contribute as much as 10GW by 2030 and up to 40GW by 2050. The Carbon Capture and Storage Association (CCSA)¹² have set a more ambitious target of 20-30GW of CCS to be deployed by 2030 (DECC, 2012b, CCSA, 2011). The plans set out by the government for CCS in its CCS Technology Roadmap indicate that this ambition is achievable subject to CCS demonstrating its effectiveness as a cost competitive low carbon generating technology in time to meet projected demand (DECC, 2012b).

Estimates completed for the UK government by (MottMacDonald, 2010, MottMacDonald, 2012) suggest that the levelised cost of electricity¹³ from plants fitted with CCS may be higher than that produced from nuclear plants but cheaper than that produced from some competing renewable sources such as offshore wind. The UK government (2012b) suggest that the inclusion of CCS in the UK energy mix also has the potential to increase the total amount of low carbon capacity given the constraints (e.g. intermittency and the inability of certain technologies to be ramped up and down according to demand) and inherent risks associated with the deployment of other technologies. They further suggest that *'CCS will contribute to diversity and security of electricity supply'* (DECC, 2012b) and that *'fossil fuel generation is also important, for diversity and for operation of the network, and because it could come on stream faster*

¹² CCS Industry Representative

¹³ Levelised Cost of Electricity refers to the average cost over the lifetime of a plant per MWh of electricity generated. This reflects the costs of building a generic plant for each technology. Revenue streams are not considered. DECC 2012d. Electricity Generation Costs. London: Department for Energy and Climate Change.

than nuclear power; development of carbon capture and storage (CCS) would be important to reduce emissions' (HL, 2008), comments echoed by both industry which suggest that *'new, more efficient, coal-fired capacity is justified to ensure the diversity of energy sources we need to provide secure and affordable energy supplies... we recognise that new coal-fired power generation still gives rise to significant CO₂ emissions, and therefore carbon capture and storage (CCS) will be required in the longer term...'* (HC, 2008), the CCSA (CCC, 2008) who identify CCS as being important for the diversity of the electricity generating system and the UKCCSC and UKERC who suggest that *'a greater diversity in fuels is typically expected to increase our overall fuel security'* (UKERC/UKCCSC, 2010).

However, despite the potential advantages of CCS and the heavy reliance placed upon it in low carbon scenarios, the technology remains commercially unproven with only chemical process plants in operation. The first two full-scale power demonstrations are under construction in North America and as a result, there is considerable uncertainty about its future viability, performance and cost and hence considerable risk associated with both private investment and policy support.

2.6 The current status of CCS in the UK

The UK government committed under the Coalition Agreement (2010) to continue public sector support for CCS (started by the previous Labour government), owing to the perceived importance of the technology and the urgency of near-term demonstrations at the commercial scale. The Coalition Agreement put forward proposals later in 2010 for a demonstration programme of four commercial-scale projects with the aim of allowing the UK to gain experience in different capture technologies, as well as the transport and injection of CO₂. In the spending review that followed the government committed £1 billion towards the capital costs of the first demonstration project, with the funding for the further three projects to be decided at a later date.

Prior to the Coalition Agreement, the previous Labour government had set in motion a procurement process under which the power industry were able to apply for financial

support to bring the first fully integrated CCS plant to the UK. The selection process¹⁴ for the first project was launched in 2007 with the objective of demonstrating the technology considered to have the most global relevance - leading to the conclusion that this should be restricted to coal plants only using post combustion carbon capture technology. This rationale was subsequently reassessed, with the 2nd progress report by the CCC recommending that gas plants also be included in projects 2-4 and agreed by the Coalition (DECC, 2010b). The aim at the launch of the selection process was that by 2011 the contracts for funding would have been signed. However, the two companies (EON and Scottish Power) that reached the latter stages of the selection process withdrew in 2010 and 2011 respectively; hence the decision to pursue this project was reversed.

Following their withdrawal, both companies completed Front End Engineering Design Studies (FEED) to enable lessons to be learnt regarding cost, design, end-to-end CCS chain operation, health and safety, environment and consent and permitting. From these studies it was highlighted that there was a lack of clarity surrounding DECC's commercial position, specifically relating to the sharing of risk and the project's overall finances which DECC suggested led to unrealistic expectations on the behalf of the suppliers in relation to the nature of any financial contractual arrangements (DECC, 2012b).

Building on the lessons learnt from the failure of the first demonstration project the current UK CCS Commercialisation Programme Competition was launched on the 3rd April 2012 with the aim of supporting practical experience in the design, construction and operation of CCS. This programme was designed to enable private sector companies to make investment decisions to build CCS equipped fossil fuel plants that are competitive with other low carbon generation technologies (DECC, 2012a).

The competition closed on the 3rd July 2012 with a total of eight bids, five of which were full chain bids (capture, transport and storage)) and three of which were part chain bids (i.e. capture or transport or storage) for the £1 billion capital funding which the government has already committed to the programme (rolled over from the failed

¹⁴ The financial procurement process under which industry were able to apply for financial support to bring forward the first fully integrated commercial-scale CCS demonstration project in the UK

project discussed above). Funding may also be possible via the New Entrant's Reserve (NER300). This is a European funding programme offering grants to installations of innovative renewable energy projects and up to 12 CCS projects. Funding for the grants will come from selling up to 300 million carbon allowances (EU ETS allowances¹⁵) on the carbon market. These allowances are taken from the NER, a set aside amount of allowances granted to new companies starting up an activity that entitles them to free allowances under the Emissions Trading Scheme. Two thirds of the money generated from the 300 million allowances will be made available to finance projects selected from a first call of proposals and the remaining third following a second call¹⁶. (DECC, 2013b, NER300, 2010). However, no CCS projects were awarded funding following the first call made by the NER300. There are further calls to be made and CCS still has the opportunity to gain funding in this way.

On the 30th October 2012 the government announced that four of these bids were to be taken forward for an intensive phase of negotiations. In March 2013, the two preferred bidders were announced, with two bids serving as reserve projects. The preferred bidders were:

1. The Peterhead Project in Aberdeenshire, Scotland involving Shell and Scottish and Southern Electric (SSE). This aims to capture 90% of the CO₂ from part of SSE's existing gas-fired power station at Peterhead, with transport to a depleted gas field in the North Sea.
2. The White Rose Project in Yorkshire involving Alstom, Drax Power, BOC and National Grid. This aims to capture 90% of the CO₂ from a new super-efficient coal-fired power station, located at the site of the existing Drax power station, before transporting to a saline aquifer in the North Sea.

¹⁵ EU ETS Allowances are a tradable emissions allowance allocated to participants in the market (i.e. power stations, industrial plants) which works on a 'cap and trade' basis. Allowances are allocated to participants via a mixture of free allocation and auction and participants must monitor their emissions annually and surrender sufficient allowances to cover their emissions. Participants are able to do this by either taking measures to reduce their emissions purchasing further allowances from other participants DECC. 2013a. *Participating in the EU ETS* [Online]. Department of Energy and Climate Change. Available: <https://www.gov.uk/participating-in-the-eu-ets> [Accessed 05/06 2013].

¹⁶ This expected revenue stream generated from these allowances is much less than originally anticipated due to a cumulative surplus of allowances (more than 2 billion at the end of 2012) reflected in a low carbon price which does not provide investors with sufficient incentive to invest and increases the risk of carbon lock in. EC. 2013. Emissions Trading: 2012 saw continuing decline in emissions but growing surplus of allowances. *European Commission Press Release*, BELLONA. 2013. *EU launches broad discussion on energy and climate policy goals for 2030* [Online]. Available: <http://bellona.org/ccs/ccs-news-events/news/article/eu-launches-broad-discussion-on-energy-and-climate-policy-goals-for-2030.html> [Accessed 26/07/2013].

Following this announcement the government entered discussions with the two preferred bidders with the aim of agreeing terms for Front End Engineering Design Studies that will last approximately 18 months. Following the results of these studies a final investment decision will take place in early 2015 for the construction of up to two projects (DECC, 2013b).

2.7 Chapter Conclusion

This chapter has introduced Carbon, Capture and Storage technologies, the form these technologies take and the reasons for their development. It has also outlined the context for these technologies both from an international perspective as well as from the UK perspective.

The next chapter provides the theoretical framework for the thesis. It begins by introducing the concept of diversity, including its origins and the development of the idea across different academic disciplines. It then goes on to discuss the relevance and importance of diversity to both energy policy in generally with a specific focus on UK electricity policy.

CHAPTER 3. Energy Systems Diversity

3.1 Chapter Introduction

This chapter introduces the concept of diversity and begins by exploring its multi-disciplinary origins. It discusses the various indices that have been used in attempts to quantify diversity across disciplines and explore their limitations. This leads on to introducing Stirling's Diversity Heuristic and how it seeks to address the limitations identified with other indices and also considers the limitations of an alternative parametric¹⁷ approach to quantifying diversity. The chapter then goes on to explore the relationship between diversity and UK energy policy, firstly by exploring diversity in the context of UK energy security and secondly by exploring how diversity has been applied to UK energy policy to date. The chapter then concludes by summarising how diversity will be applied in the context of this thesis.

3.2 What is Diversity?

A general characterization of diversity has been provided by a number of natural and social science disciplines including business and management studies and mainstream economics (see Table 1). The various disciplines provide a number of empirical and theoretical perspectives on diversity, but a common theme is that diversity can be related to the '*the nature of degree of apportionment of a quantity to a set of well-defined categories*' (Leonard, 1989).

In light of this, Stirling (2008) suggests that this simple and somewhat summary definition raises three important questions as to exactly what constitutes a '*quantity*'? which he seeks to address by posing three further questions:

1. How many categories constitute a '*set*' and how disaggregated should they be?
2. How can we characterize the '*nature of degree*' of apportionment between categories?
3. What criteria are employed in making distinctions between categories?

¹⁷ Parametric refers to the assumption of the value of a parameter for the purpose of analysis

Different disciplines place different emphases on each of these questions. For example, ecological disciplines tend to focus on questions regarding category counting and apportionment whereas in evolutionary biology, attention tends to be directed towards defining the categories employed in the analysis of diversity. Similarly in conservational biology, problems of global biodiversity loss divert attention to the prioritisation of rare species in terms of the degree to which they preserve unique genotypes¹⁸ of phenotypes¹⁹ (Stirling, 1998, Eldredge, 1992). Therefore, in developing a robust general characterization of diversity it is important to consult with a wide range of empirical and theoretical perspectives (Stirling, 1998).

The questions Stirling raises from his review of diversity across disciplines help to form the basis of his definition of diversity, based upon three mutually distinct properties: *variety*, *balance* and *disparity*. Stirling (1998) proposes that the concept of diversity, despite the different emphases across disciplines, relates to '*the nature or degree of apportionment of a quantity to a set of well-defined categories*'. Each of these properties is: a) able to vary independently; b) is both necessary and fundamental in the constitution of the other two properties; and c) is insufficient by itself as a characterisation of diversity (see Figure 4) (Stirling, 1998).

- *Variety* is used to refer to the number of diverse categories of '*option*' into which a system may be divided. For example, in the case of the UK electricity generating system '*coal*', '*gas*', '*nuclear*' and '*wind*' may each represent an energy '*option*'. The greater the number of energy '*options*' the greater the variety of the system and so with all else equal the diversity of the system is greater (Stirling, 2010). This category is quantified simply by counting the number of energy '*options*' in the energy system of interest.
- *Balance* refers to the proportion of the system assigned to each category identified within '*variety*'. More simply put, to what extent do we rely on each energy option? For example, what proportion of the system is contributed to by each energy '*option*'? The more equal the balance across the different '*options*' the greater the system diversity. Balance has been easily quantified using a number of

¹⁸ Genotype refers to the genetic constitution of an organism

¹⁹ Phenotype refers to the observable characteristics of an organism arising from the interaction of its genotype with the environment.

indices (Simpson, Shannon and Weaver) which are discussed in more detail in section 3.3.2.

- *Disparity* refers to the manner and degree in which different options may be distinguished and addresses the question ‘*how different are the options from one another?*’ For example, how different is coal from gas and gas from nuclear. Quantification of disparity is difficult and as a result this property has often been neglected in the literature.

Table 1 – Conceptions of diversity within different academic disciplines

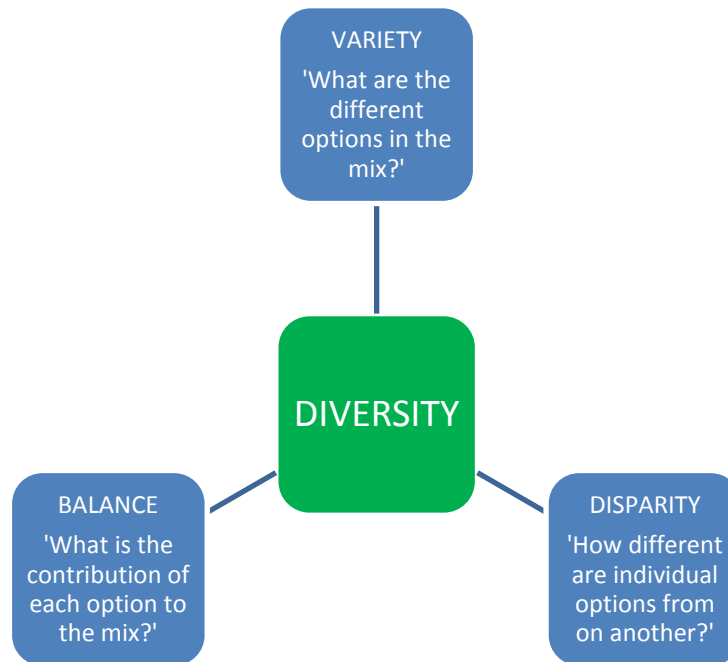
Discipline	Inter-discipline	Author/Reference	Context
Natural Sciences	Mathematical Ecology	Pielou 1977, Magurran 1988	Ecological Diversity and its Measurement
	Conservational Biology	Forey, Humpheries and Vane Wright 1994	Assessment of Diversity by Summation
	Pharmacology	Bradshaw 1996	Diversity in chemical screening for drug development
	Environmental Evolution	Swanson 1994	Biodiversity conservation and plant genetics
	Palaeontology	Runnegar 1987, Gould 1989	Evolution of the Mollusc
	Taxonomy	Sneath? and Sohal 1973	Principles of numerical taxonomy
Social Sciences and Humanities	Psychology	Junge 1994	The diversity of ideas surrounding diversity measurement
	Archaeology	Leonard and Jones 1989	Quantification of Diversity in Archaeology
Business and Management	Financial Management	Lumby 1984	Diversity in investment appraisal
	Economics	Saviotti 1996	Technological evolution and the economy
	Complexity Theory	Kauffman 1993	Self organisation and selection in evolution

Source: (Stirling, 1998)

Such difficulties arise from the partly subjective nature of disparity, particularly as judgments made to determine disparity have knock on effects, which underlie the characterizations of variety and balance. Applications of portfolio theory have been applied in an attempt to overcome this (see section 3.3.1). Another approach to

quantifying disparity has included some kind of scalar measurement such as Euclidean distances, which will be explored further in section 3.2.1.

Figure 4 – Schematic illustrating the three properties of diversity; variety, balance and disparity



Source: adapted from (Stirling, 2010)

Hence, Stirling argues that diversity consists of three properties, each of which is fundamental and necessary to capture diversity in a comprehensive way (Stirling, 1998). The interdependency of these properties leads to difficulties in the application of existing diversity indices, which focus exclusively on subsets of these three properties. The importance of all three properties is illustrated in the following example; an electricity system might be apportioned into four categories called ‘coal’, ‘gas’, ‘nuclear’ and ‘renewables’, but ‘renewables’ may require further subdivision into other ‘nested’ categories e.g. ‘wind’, ‘solar’, ‘biomass’, and ‘tidal’. However, the variety and balance of this system cannot be characterized without first partitioning the system based on its disparities. In principle, the disparities between the ‘nested’ categories may be greater than the disparity between the aggregate categories such as nuclear and gas plants (Stirling, 2010). Therefore resolving balance and variety requires the consideration of disparity. This illustrates that each of the properties

alone are insufficient as they are all necessary for the constitution of each other. However due to the nature of disparity, this property is often neglected in the diversity literature.

Table 2 – Diversity indices in different fields and disciplines

Coefficient	Application	Attributed Property
Gini (1912)	Economic statistics, wealth and distribution	Balance
Simpson (1949)	Ecological Sciences: Biological Diversity	Variety and Balance
Herfindahl-Hirschman (1945)	Economics: measuring market concentration	Variety and Balance
Shannon-Weiner (1962)	Communication theory	Variety and Balance
Rao (1982)	Population Biology	Variety, Balance and Disparity
Stirling (1988) - quadratic	General application to energy systems	Variety, Balance and Disparity
Stirling (2007) – generalized	General application to energy systems	Variety, Balance and Disparity

Source: (Skea, 2010)

3.2.1 Measuring Disparity

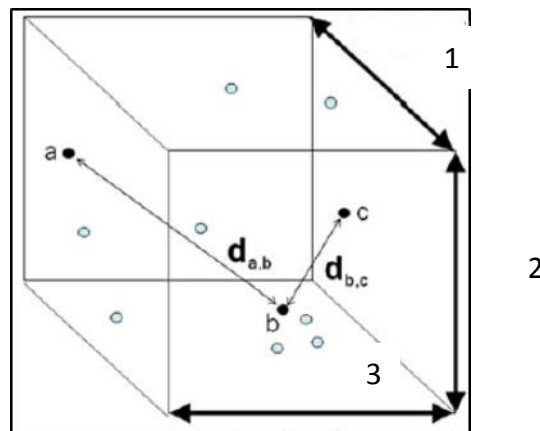
As discussed, variety and balance are relatively arbitrary and easy to quantify because they depend on the definition of options which are well defined and easy to compute once defined. Disparity, however, has proven much harder to quantify in the literature. This is because disparity reflects the underlying attributes of a system. In the context of energy systems this may include capital costs, technology class, and geographical origin of fuel supply or environmental impacts for example. Since different individuals or organisations may select different attributes, or place different weightings on those attributes disparity is an intrinsically subjective measure. Thus, if disparity measures are to be considered in the measurement of diversity, then the values of individual attributes should be assigned using a deliberative process (Skea, 2010).

Disparity as defined earlier in section 3.1, refers to the manner and degree in which different options (in this context, electricity generation options) can be distinguished and the difference between these two options can be represented as co-ordinates in a multi-dimensional ‘disparity space’ (Stirling, 2007, Stirling, 2010). In section 3.3.3,

disparity is referred to as d with the disparity between two options (i and j) referred to as d_{ij} with values between 0 and 1. In order to determine the distance between i and j there are two possible approaches that can be taken.

The first approach suggests that different disparity attributes may be weighted to reflect judgements of their relative importance and the Euclidean distances separating these options can be used to reflect their mutual disparity. Appropriate normalisation and weighting can be constructed to accurately reflect any conceivable perspective on the different features of the different options (Stirling, 2010). To determine this distance, this approach developed by Rao (1982b) and built on by Ricotta (2004) and Stirling (2007), takes the distance between two options for each individual attribute and then combines them in n -dimensional Euclidean space using a sum of squares approach. Thus $d_{ij} = \sqrt{(\alpha_1^i - \alpha_1^j)^2 \cdots (\alpha_N^i - \alpha_N^j)^2}$ where α_x^i is the value of attribute x for option i (Skea, 2010).

Figure 5 – Mockup of a stylised disparity space



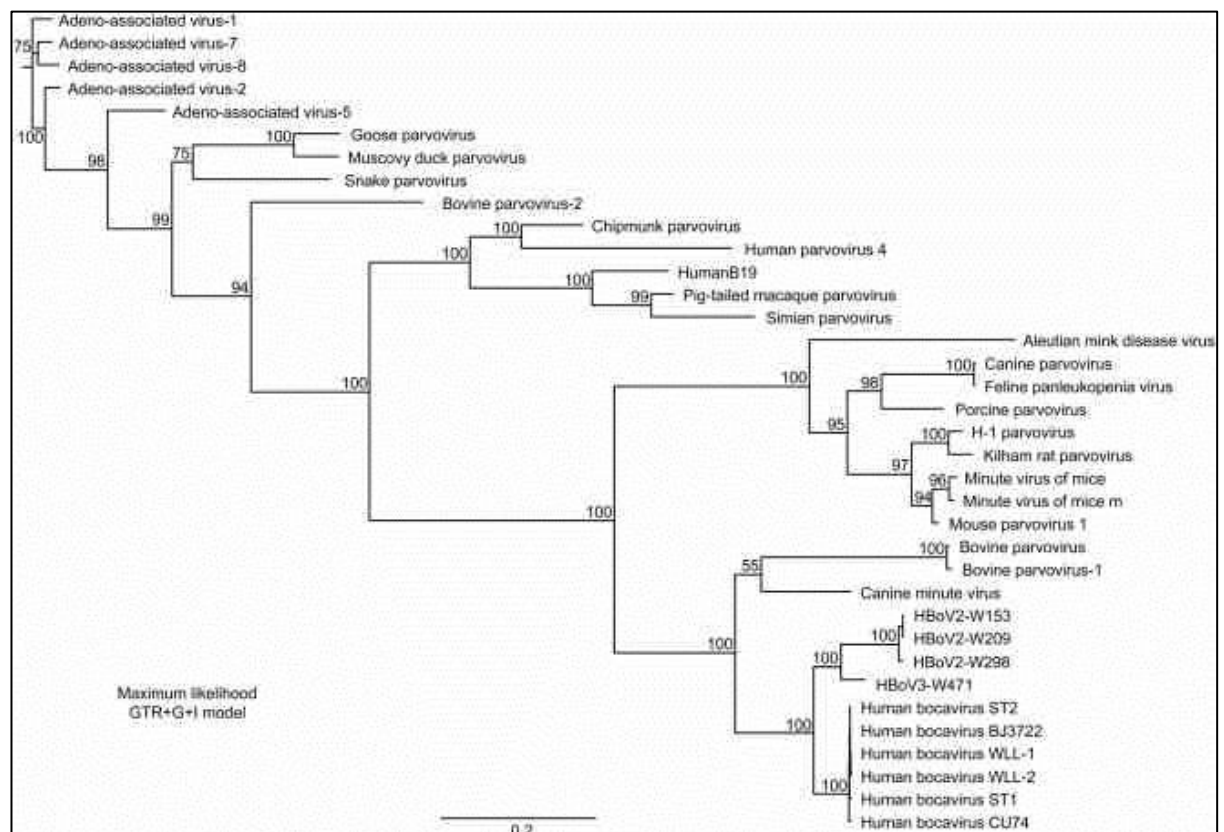
Note: This mockup of a stylised disparity space is based on normalised performance data of electricity generating options represented in a reduced 3-dimensional space with d representing the disparity space between technology options and b or b and c . Each dimension represents a different criterion within the performance data. For example, criterion 1 may refer to technology cost data, criterion 2 to electrical efficiency data and criterion 3 to plant lifetime data.

Source: (Stirling, 2010)

A branching structure such as a dendrogram (tree diagram) can be used. This technique is frequently used in evolutionary biology and taxonomy and developed by Weitzman (1992). A dendrogram shows using a series of lines the relationships

between the options of interest which in the context of energy systems refers to the mutual disparities of a series of energy options based on the technologies performance data. The disparity between two options is measured by the distance between the two measured from left to right along the tree (see Figure 6).

Figure 6 – The evolutionary development of Parvoviruses according to their genetic sequences



Note - Dendrogram showing the indicative disparities between a family of parvoviruses according to their genetic sequences. The disparity is measured between two parvoviruses by measuring from left to right along the tree.

Source: (Arthur et al., 2009)

3.3 Methodologies for characterising Diversity

As identified in section 3.2 there are different theoretical underpinnings of diversity within the electricity systems literature. The first, is a 'parametric approach' derived from Financial Portfolio Theory (Awerbuch and Berger, 2003a, Berger, 2003, Roques, 2006) and is concerned with the volatility of fuel costs associated with different energy portfolios and assigns probabilities to characterized future events (Awerbuch and

Berger, 2003b). It is assumed that the expected costs of different supply options are known, as are the expected levels of fuel price volatility. Using standard statistical methods it is possible to derive 'efficient' sets of energy portfolios which trades-off expected costs and risk. This literature builds on already established practices of defining efficient risk-reward frontiers in building up portfolios of financial assets (Skea, 2010). This approach to diversity has been used to derive 'optimal' trade-offs between the expected (mean) levels of cost or profits and the volatility (variance) of those costs or profits (Awerbuch and Berger, 2003b, Berger, 2003). This is discussed in more detail and critiqued in the next section (3.3.1).

The second non-parametric approach explores the issue of 'diversity' in energy supply and the derivation of quantitative diversity indicators (Grubb, 2006, Jansen et al., 2006, Stirling, 1994b, Stirling, 2010). This approach has used a range of disciplines to explore the theoretical underpinnings of 'non-parametric' indices of system diversity (non-parametric indices require no prior knowledge about measures of cost or volatility required in the previous approach using financial portfolio theory). This is particularly relevant under circumstances of '*uncertainty*', described by Stirling as '*ignorance*' where we are unable to fully determine contingencies against which we are planning (Stirling, 1994b) or as Rumsfeld (2002) put it '*we don't know what we don't know*'.

This approach to diversity has been applied to energy systems in two different ways. Firstly, it has been applied descriptively with changes in levels of diversity associated with changes in historic technology/fuel mix, or to project future changes (Grubb, 2006). Secondly it has been applied with deliberative processes whereby trade-offs between portfolio diversity and the intrinsic features of individual technology options have been explored (Stirling, 2010, Yoshizawa, 2009). This has been achieved by conducting in-depth interviews to elicit information characterising divergent perspectives on the performance and distinguishing attributes of a wide range of electricity generating options using Multi-Criteria Mapping (MCM) and Multi-Criteria Diversity Analysis (MDA) methodologies (Stirling, 2010, Yoshizawa, 2009). This second application is not used to determine an 'optimal' mix of options but rather to explore

subjectively the valuation of technology attributes and the value that is attached to diversity so that it can be clarified and further explored (Skea, 2010).

3.3.1 Parametric Approach - Mean-Variance Portfolio Theory

Mean-variance portfolio (MVP) theory was introduced by Markowitz in 1952 as a financial theorem and enables the creation of minimum-variance portfolios (a portfolio comprised of assets perceived as risky with the least variance for any given level of expected (mean) return on the investment). Such portfolios minimise risk so that no unnecessary risk is taken relative to expected return and this is as measured by the standard deviation of periodic returns. The idea behind this, more simply, is that while investments are unpredictable and as a result involve a certain degree of risk, the movement of individual assets which generate different expected rates of return can be used to insulate the portfolio as a whole leading to higher returns with little or no further risk (Awerbuch and Berger, 2003a).

In the context of energy generating technologies the principles derived from financial portfolios can be applied to portfolios of generating assets in which market or historic cost risk can be used in place of and in the same way as it is for financial assets. For example, in this instance, market risk is measured on the basis of the historic variation of the cost of the technologies (regarded as assets) to be considered.

The application of MVP theory to generating assets in this way has attempted to identify optimal technology fuel portfolios either via regulated utilities or from a national perspective. These studies have focused on the production costs of different generating technologies and define portfolio return as the reciprocal of unit generating costs i.e. the reciprocal of cost per kWh and price risk in terms of fuel price volatility per year. The subsequently generated optimal portfolio of generating assets is determined by projected unit costs and projected patterns of variance of different fuel types. Efficient portfolios of generating assets are those that expose society and or the investor to the minimum level of risk needed to attain energy cost objectives keeping the lights on (Awerbuch and Berger, 2003a, Roques et al., 2007).

A critique of these studies by Roques (2007) suggests that in fact this methodology is not appropriate for looking at liberalised energy markets such as the UK (in which the

electricity market experiences a strong correlation between electricity and gas and coal prices). This is because liberalised markets are unlikely to reward a diverse fuel supply sufficiently to make the choices of private investors align with a socially optimal fuel mix, unless long term power purchase agreements with complementary risk profiles are made available.

A further critique by Stirling (1994b) also disregards the applicability of MVP theory as a study of diversity. Stirling argues that fuel price movements (fundamental in determining generation costs) are unpredictable and that *'decisions in the complex and rapidly changing environment of electricity supply are unique, major and irreversible'* and that *'ignorance rather than risk or uncertainty dominates real electricity investment decisions'*. His conceptualisation of diversification is a response to ignorance (Awerbuch and Berger, 2003b).

Before moving on further, it is important to thoroughly consider the ideas of ignorance, risk and uncertainty as they are particularly applicable to electricity appraisal investment decisions that use probabilistic techniques such as MVP theory. It is in the recognition of the limits of probabilistic techniques in such decision making that it is sometimes necessary to distinguish between ignorance, risk and uncertainty which is why it is necessary to consider these terms in more detail. Stirling (1994a) suggests that *'ignorance exists where there is no basis upon which to assign probabilities to outcomes, nor knowledge about many of the possible outcomes themselves'*, more simply *'we don't know what we don't know'* (Rumsfeld, 2002).

This is particularly poignant in the context of electricity supply investments where technologies such as CCS which are taken into consideration are not yet commercially proven and so there is little basis for the assignment of probabilities in investment decisions due to the lack of information available compared with mature technology options which leads to more associated risk with respect to estimates of cost and efficiency for example. In the same light, it is next important to distinguish between the terms risk and uncertainty. Risk is referred to by as Stirling as *'a probability density function which may meaningfully be defined for a range of possible outcomes'* and uncertainty exists *'when there is no basis upon which to assign probabilities'*. If, as we

have already suggested that we don't always know what all of the possible outcomes of a decision are then this will be accompanied by a high level of risk and subsequent uncertainty. This is because if '*we don't know what we don't know*' then we are unable to assign probabilities as MVP theory would suggest, to technologies such as CCS, in electricity investment decisions.

With these ideas in mind, Awerbuch and Berger, authors of MVP studies of electricity generating assets respond to this critique by suggesting that portfolio risk is defined as total risk which is measured as the standard deviation of periodic historic returns (in this case of fuel price) and therefore includes fluctuations of individual portfolio components which may in fact be attributable to a variety of historic causes. Subsequently total risk can be seen as the sum of the effects of all historic events (including unexpected historic events). Awerbuch and Berger suggest that while no random event may be duplicated, in the case of equity and stocks, historic variability is widely considered to be a useful indicator of future volatility and suggests that this is no different for fossil fuel prices, O&M outlays and investment period costs. However, the authors do point out that certain fundamental changes in the future such as new technologies or market restructuring could create 'surprises' by altering observed historic risk patterns and that such changes are unpredictable. In response to such changes, Awerbuch and Berger suggest that these possibilities should not drive a decision approach and they find it more plausible to assume the totality of random events over the past three decades sufficient to cover the reasonable range of expectations for the future. It is on the basis of the argument put forward by Stirling that the selection of his Diversity Heuristic as opposed to MVP theory will be used for this thesis, in the main because CCS technologies, the set of technologies focused upon in this thesis have no past from which to draw upon.

3.3.2 Non-parametric approach - Diversity Indices

As indicated, the notion of diversity has been developed within a number of fields across a range of disciplines along with quantitative indicators of diversity. These have historically focused on variety and balance since they are easier to quantify, with the Gini and Simpson indices being notable examples, which are discussed in more detail

in the following section. These two indices are subsequently drawn upon in Stirling's Diversity Heuristic, which in addition considers disparity. A further index, which also considers variety and balance only, the Shannon-Wiener index will also be introduced because of its relevance to the UK Energy Security Strategy (2012) discussed in more detail in 3.4.2.

3.3.2.1 Gini and Simpson Indices

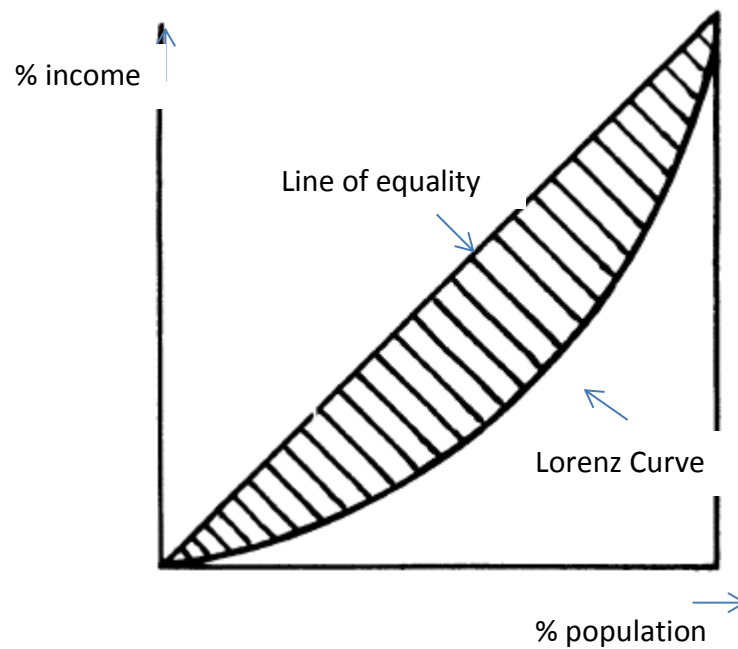
Gini (1912) devised a measure of statistical dispersion which measures the inequality among values within a frequency distribution. This measure is most commonly applied to the analysis of income distribution across a population and is referred to as the Gini coefficient and mathematically defined using the Lorenz Curve.

The Lorenz Curve measures inequality by plotting the proportion of income against the proportion of the population, both expressed in terms of percentages. The Gini coefficient is equal to the area between the line of perfect equality and the Lorenz Curve divided by the entire triangular area under the line of perfect equality and hence is a measure of diversity, where variety refers to the individuals within the population and balance refers to the proportion of income associated with each member of the population.

This can be represented graphically (see Figure 7) or with the formula:

Equation 1

$$1 - \sum_{i=1}^N p_i^2$$

Figure 7 – Lorenz Curve

Source: (Gastwirth, 1972))

The same index was published as a measure of biodiversity in the ecological literature by Simpson (1949) who was unaware of the paper published by Gini. This followed papers by Yule (1944) and Fisher (1943) which suggested a '*characteristic*' and an '*index of diversity*' respectively, which were measures of the '*degree of concentration of diversity*' achieved when the individuals from a population are classified into groups within logarithmic distributions (Simpson, 1949).

The defining aim of this index is to explore the attributes of variety (individuals within the population) and balance (the concentration of individuals within a population) and may arguably be better referred to as a measure of concentration as opposed to a measure of diversity due to the inability to distinguish between how different individuals are within a population are; instead referring more broadly to the concentration of one type of individual within that population.

It is summarised in the following form:

Equation 2

$$\sum_{i=1}^N p_i^2$$

Where p_i refers to the proportion of the population comprised of individual i . Translated across to energy systems, then we might assume that p_i refers to the proportion of electricity generation from option i which in this instance may refer to a specific generating technology or fuel type.

3.3.2.2 The Shannon-Wiener Index

Equation 3

$$1 - \sum p_i^2$$

The Shannon-Wiener Index is defined in Equation 3 and is commonly applied in the ecological literature but originally developed by Claude Shannon, a mathematician. This measure allows the quantification of the information content of strings of text in which the original idea was that the more different letters there are, and the more equal their proportional abundance in a particular string of interest then the more difficult it becomes to predict the next letter in the string (Shannon and Weaver, 1962, Shannon, 1948). Therefore translated across to energy systems, p_i in the context of the Shannon-Wiener index may be assumed to be the proportion of the electricity generation system comprised of option i which for example may refer to a specific technology as was the case for the Simpson Index. Similarly to the Simpson index, this index may be arguably an index describing concentration as opposed to diversity, due to the inability within the index to capture the difference between the energy options in the system and instead simply measures only the 'concentration' of energy each energy option.

3.3.3 Stirling's Diversity Heuristic

As we have seen, the Gini Simpson and Shannon-Wiener indices, consider just two of the three properties of diversity, variety and balance. Stirling's framework uses a quantitative heuristic which incorporates his ideas and assumptions surrounding the various aspects of diversity into a heuristic which he suggests '*is essentially a strategy which uses experience-based techniques for problem solving offering an explicit, systematic basis for exploring sensitivities to the assumptions*' (Stirling, 2007)) to assess diversity which also takes into consideration the third property of diversity; disparity.

Disparity is an important property in the context of electricity generation because there are a large variety of technologies that can contribute to generation and each of these technologies has a number of attributes, which distinguish it from all the other technologies. For example, with reference to CCS, this is not a single technology but a set of technologies, which operate using different fuels i.e. coal, gas or biomass, have different capital costs and different fixed and variable O&M costs for example. Therefore by excluding disparity from the assessment of diversity, an incomplete picture of diversity is generated, hence the choice of Stirling's diversity heuristic for this thesis.

The starting point for this heuristic is referred to as the '*sum of pairwise option disparities*' (D) and is weighted in proportion to option contributions and derived independently from different disciplines (Stirling, 1998, Stirling, 2010, Rao, 1982a).

Equation 4

$$D = \sum_{i (i \neq j)} d_{ij} \cdot p_i \cdot p_j$$

The different options in the energy system (variety) are represented by i and j and the proportion contribution of each of these options (balance) is reflected in p_i and p_j . The disparity of these options is reflected by d_{ij} , which is the distance separating option i and j in disparity space (see for more detail). This formula is then summed across the half matrix of non-identical pairs of options ($i \neq j$) (see Equation 4) i and j with identical pair options excluded and in instances where d_{ij} is equal; D reduces to one half of the Gini coefficient (see schematic below).

Figure 8 – Example matrix of energy options

	i	j	k	l
i	ii	ij	ik	il
j	ji	jj	jk	jl
k	ki	kj	kk	kl
l	li	lj	lk	ll

Note – matrix of energy options i, j, k and l . Identical pair options are high lighted in yellow and not included in the summation. Each half of the matrix contains identical pair options, thus to avoid doubling up, summation is only necessary across half of the matrix. In the instances where d_{ij} are equal, Gini is reduced by half because you are essentially talking about technology options that are the same (no disparity space between the two) and so to avoid counting the same values twice i.e. i and j you use half Gini to represent the heuristic.

Stirling's diversity heuristic does not end here; it can be further extended to explore the question 'how much diversity do we actually need in the UK electricity system?' This could be explored by generating 'optimally diverse technology portfolios' using an extension of the heuristic used in this thesis, which would allow an optimal technology portfolio under various input assumptions to be derived from the data.

In the derivation of 'optimal technology portfolios' then the system-wide properties of diversity are taken into consideration, building on the heuristic applied in this thesis. More specifically, the overall strategic performance of the technology portfolio as a whole will be a function of other system properties and the performance of individual energy options. More simply, such portfolio effects may arise from interactions between subsets of options such as financial costs, operation efficacy, environmental impacts or wider economic factors.

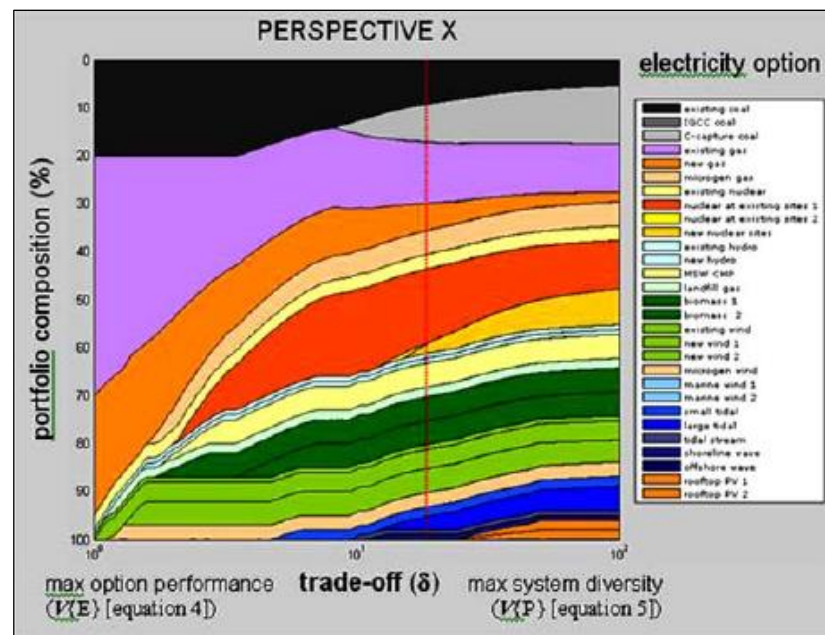
To take these factors into consideration then the value assigned under any given perspective to any particular energy system under specific conditions, referred to as $V(S)$ can be expressed as the sum of the value of the aggregate performance of individual energy options, referred to as $V(E)$, and the value attached to irreducible portfolio-level properties including diversity $V(P)$ (Stirling, 2010).

Using, this extension of the heuristic $V(S)$ can be used to systematically explore the different perspectives and assumptions concerning the contributions of $V(E)$ and $V(P)$

to the system, which can also be referred to as a diversity-performance trade-off. For each perspective on the available technology options there will exist an apportionment of options that yield a maximum overall value and by varying $V(S)$ between zero and affinity a set of all possible conditionally optimal energy systems are generated. This will range between a maximum value for the aggregate performance of energy options to those that maximise value due to portfolio interactions and system diversity (Stirling, 2010), see Figure 9 for an illustration of how $V(E)$ and $V(P)$ are plotted in order to ascertain $V(S)$.

However, this is outside the scope of this thesis and will not be expanded on here. Further detail can be found in Stirling (1994, 1998 and 2010).

Figure 9 – Example plot showing the optimal performance-diversity trade-off for a single perspective on UK electricity system options



Source: (Stirling, 2010, Yoshizawa, 2009).

3.4 Diversity and UK Energy Policy

3.4.1 Energy Security and Diversity

Concerns about the security of energy supply feature centrally in UK energy policy, particularly in relation to technological and fuel diversity. However these concerns are not new and have been a practical concern for the UK at least since World War II when energy security was closely tied to the supply of fuel for military purposes. Prior to

World War II the British Navy moved from domestically sourced coal to imported oil making it more vulnerable to attack. In the presence of war the idea of diversity of supply to ensure security of supply emerged when Winston Churchill suggested that the *'safety and certainty of oil lies in variety and variety alone'* (Yergin, 2006, Cherp and Jewell, 2011).

The concept of energy security is deeply embedded in discussions surrounding energy issues and climate change not only in the UK but also at a global level. However, despite extensive discussion, little attention has been paid to gaining a deeper understanding of the term, with the result that references to energy security are frequently abstract, elusive and vague (Chester, 2010). However, this thesis is not concerned with addressing this gap but instead seeks to draw on the notion of energy security to explore its relationship with diversity.

Therefore for the purposes of this thesis we shall refer to a definition set out in the recent government's Energy Security Strategy 2012. This suggests that energy security relates to ensuring we have access to the energy services we need by providing physical security, at prices that avoid excessive volatility and help to ensure price security. This document also recognises that energy security is a complex issue and that definitions of energy security should be flexible and should not be limited to simply securing energy supplies but also include delivering the end-products UK consumers need such as heat, power and transport (DECC, 2012e).

As highlighted, discussions of energy security in the literature are extensive and there are many studies, which have sought to integrate long and varied lists of energy security concerns by classifying them into different 'dimensions' or 'aspects' of energy security. However, Cherp and Jewell (2011) suggest that while such classifications may help to attract the attention of policy makers and the general public to the different facets of energy security, that these studies are only the 'first step' in developing a systematic and scientific understanding of the challenges of energy security. This is on the basis that the classifications generated in these studies are rarely systematically justified and that by placing several concerns into a single group does not necessarily help with understanding the challenges or help to develop integrated solutions.

Cherp and Jewell (2011) also highlight another group of studies that seeks to understand energy security by taking the route of quantification as opposed to classification, which is based on constructing various indicators. However, they highlight that these studies, despite being useful in supporting policy-making, have limitations and tend to underestimate non-quantifiable concerns, uncertainties and non-linearities.

In response to this, Cherp and Jewell (2011) identify three distinct perspectives on energy security that have emerged, all of which have arisen from initially separate policy agendas such as security of supply of fuels for military purposes and transportation, the uninterrupted provision of electricity, and ensuring market and investment effectiveness. These three perspectives have emerged from specific epistemological and policy communities in the literature which have explored energy security challenges from different perspectives with each community focusing on a specific set of problems and presenting a distinct set of policy responses. Cherp and Jewell refer to these three perspectives as the 'sovereignty', 'robustness' and 'resilience' perspectives respectively.

The 'sovereignty perspective' has its roots in political science, international relations theories and strategic security studies where issues relating to oil security, primarily for military use and later by the transport sector have shaped the perspective. The focus of this perspective has been on energy security threats posed by external actors with the main threats originating from embargoes, malevolent exercise of market power or acts of sabotage or terrorism. The analysis of this energy security from this perspective has focused on the configuration of interest, power and alliances and the space for manoeuvre between suppliers or supply options with risk minimisation in this perspective pointing towards more trusted suppliers, weakening a single agent's role through diversification, substituting imported resources for domestic resources where possible and casting military, political and/or economic control over energy systems (Cherp and Jewell, 2011).

The 'robustness perspective' has its roots in the natural sciences and engineering where the importance of energy in general and more specifically electricity, leads to

the policy challenge of ensuring the even functioning of systems that are becoming increasingly more sophisticated. From this perspective, energy security threats are viewed 'objectively' as quantifiable factors such as growth in energy demand, scarcity of resources, aging infrastructure, technical failure or extreme natural events. The subsequent minimisation of risk in this perspective involves upgrading infrastructure, moving across to more abundant energy sources, adopting safer technologies and managing demand growth (Cherp and Jewell, 2011).

They argue that the 'resilience perspective' with its roots in economics and complex systems analysis has emerged from consideration from the practical challenges of establishing functioning energy markets and ensuring effective long-term investment in energy systems and technologies. This perspective views the future as inherently unpredictable and uncontrollable due to high levels of uncertainty and the non-linearity of energy systems, markets, technologies and societies. In light of such uncertainties, this perspective views the threats as a result as highly unpredictable and may include regulatory changes, unforeseeable economic crises or booms, change of political regimes, disruptive technologies and climate fluctuations. This perspective searches for the more generic characteristics of energy systems that ensure protection against the threats outlined by spreading risk via diversity, flexibility and adaptability and does not focus on analysing, quantifying or minimising specific risks (Cherp and Jewell, 2011).

Two of the three perspectives on energy security discussed above highlight the idea of diversification as a means with which to address challenges to energy security. The rationales for these challenges can be found within the energy systems diversity literature which discusses the potential benefits of energy system diversity which are indirectly associated with energy security as discussed above. This literature is neatly summarised by Stirling (2010) who suggests four rationales that support the potential benefit of diversity in the electricity system going beyond simply ensuring security of supply. These are summarised below:

1. *Competitive diversity in energy markets* - this has been suggested to have a significant effect on the competitiveness of the wider economy (DTI, 2003) and so

reducing the concentration of a technology, service or commodity market is claimed to be important means with which to promote competition (Aoki, 1996).

2. *Fostering innovation* – diversity is claimed to be of particular value when policy becomes focused on driving radical transformations such as the transition to sustainable energy. In such instances, Rosenberg (1982), and Landau et al. (1996) argue that general technical, institutional and functional heterogeneity can help to foster innovation.
3. *Improved tailoring of energy systems* -diversity is argued to be important in the move towards sustainable energy, since allowing diverse cultural, ecological, geopolitical and geophysical conditions to be taken into account can aid this transformation (Landau et al., 1996).
4. *The accommodation of conflicting socio-economic interests* –diversity is argued to be important in helping to address irreconcilable socio-economic interests such as debates surrounding nuclear power by sustaining a variety of options and technologies (Stirling, 1997).

3.4.2 The Application of Diversity to UK Energy Policy

As mentioned in the previous section, one of the earliest references to diversity was by Churchill during World War II. Diversity is still highlighted in UK energy policy today in a similar context and over the past ten years diversity has played an important role in justifying policies in the governments Energy White Papers and reviews (see Table 3). But despite this, very little attention has been paid to what diversity means, how it can be measured and achieved and the implications of increased diversity for the energy system as a whole. A good example of this is the recent Energy White Paper of 2011, which suggests that '*investing in diversity is key to preserving and enhancing the UK's security of supply*'. However, this document does not examine how the UK should go about achieving this or indeed the potential impacts of this for the energy system.

Table 3 – Number of mentions of ‘diversity’ in UK Energy White Papers and associated documents over the period 2003 to 2012.

Government Document	No of times the word ‘diversity’ is mentioned
Energy White Paper 2003	21
Energy Review 2006	18
Energy White Paper 2007	22
Energy White Paper 2011	4
UK Energy in Brief 2012	11
Energy Security Strategy 2012	28

There are two recent and important documents, UK Energy in Brief (2012) and the Energy Security Strategy (2012) that focus upon diversity in more detail than any previous government documents. The first document provides a summary of key developments in the UK energy system, more specifically focusing on how energy is produced and the way in which energy use influences GHG emissions. The second document summarises the UK’s current position and outlines a strategy for the future of energy security policy in the UK by delivering a set of wider goals which provide resilience to disruption, make provisions for energy efficiency measures to lower exposure to energy market risks both domestically and internationally, maximise economic production of our oil and gas reserves, work to improve the reliability of global energy markets to ensure they are dependable and reliable, to ensure reliable networks are built for energy delivery and finally to support decarbonisation of our economy and thus reduce our international dependence on fossil fuels.

The UK Energy in Brief (2012), an annually published document uses the term ‘diversity’ to compare the primary fuel supply of G8 nations from 1980-2010 and has consistently quantified diversity using the Shannon-Wiener index over this period. This is despite there being no explanation given for the use of this indicator or in fact any discussion around the meaning of diversity²⁰ or indeed any discussion about the implications surrounding the diversity of fuel supplies for the G8 nations. There is however a shift occurring more recently with the Energy Security Strategy 2012, which

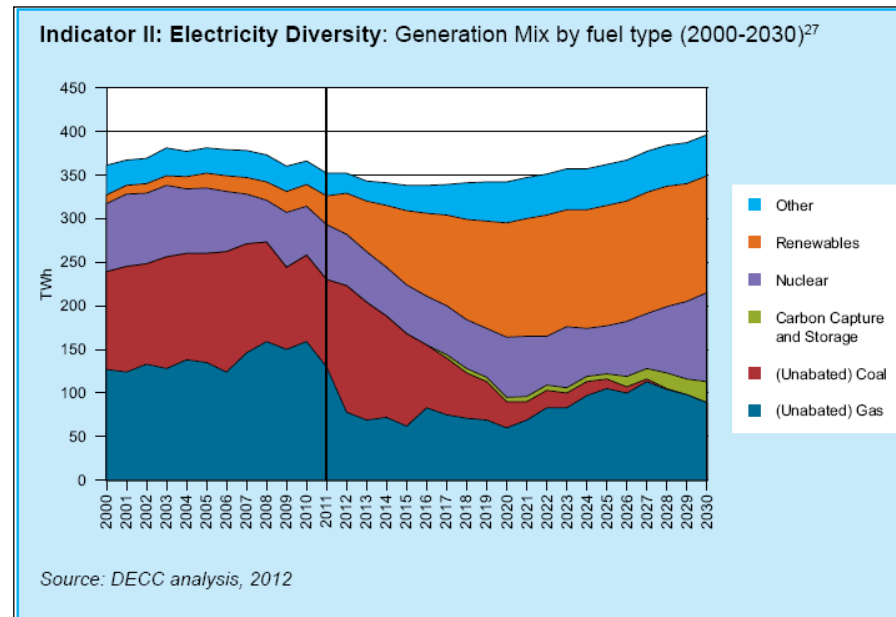
²⁰ this is reserved for the appendix and remains brief

moves away from using a single diversity index, to a series of indices that measure diversity in electricity and possibly sources of gas and oil as well as energy as a whole.

In the Energy Security Strategy's assessment of UK energy security, diversity was employed as an indicator in three ways. Firstly to assess electricity diversity according to the generation mix by visually representing this data on a graph by plotting electricity generation for each technology type against time spanning the time horizon 2000-2030 (see Figure 10). Secondly as an indicator to assess gas diversity by visually representing historic and projected capacity and demand scenarios from 2000-2030 and finally as an indicator to assess oil diversity by visually representing UK oil product imports in the form of pie charts. Such a visual representation of the diversity of the system is useful; it shows that the UK already has a relatively diverse generation mix according to fuel type. However, this qualitative description of the diversity of the UK electricity system is not underpinned by any quantitative analysis other than giving the percentage contribution from each fuel/technology. Unlike UK Energy in Brief 2012, an index is not used to quantify the diversity of the system. Therefore it is difficult to assess how the diversity of the system changes over time, nor is there any expansion in the analysis on what a diverse electricity system should look like other than our *'current generation mix is drawn from a diverse range of fuel sources'* and that a *'more diverse supply reduces overall system risk by reducing exposure to individual technology failure'*.

With these comments in mind it would be useful to have a more rigorous basis for understanding the meaning of diversity, measuring the diversity of an energy system and forming better judgements on how diverse that system should be and what trade-offs may be involved.

Figure 10 – Electricity Diversity of the UK Generation Mix by Fuel Type 2000-2030



Source: (DECC, 2012e)

3.5 Summary of the investigation of Diversity within this Thesis

This thesis will focus on the application of Stirling’s diversity heuristic to characterise the diversity of a set of scenarios to generate ‘*diversity profiles*’ which will enable the comparison of diversity both between scenarios (according to their different input assumptions) and across scenarios. The input assumptions of interest to this thesis are centred around exploring the potential impacts of the deployment of CCS technologies on the UK electricity system and will be discussed in more detail in Chapter 5.

There are two main reasons for selecting a non-parametric approach generally and Stirling’s diversity heuristic specifically:

1. The Stirling heuristic enables disparity to be taken into consideration when characterising diversity in addition to enabling the different perspectives on disparity to be incorporated into the characterisation of diversity.
2. Awerbuch and Berger (see 3.3.1) accept the limitation that new technologies (such as CCS) can place on the application of MVP theory to electricity generating assets and that the totality of random events over the past thirty years should be sufficient to account for such changes to the system. However, Stirling argues that the uncertainty associated with such changes to

the system are surrounded by ignorance. It is in fact this ignorance that drives real electricity investment decisions not risk or uncertainty and the portfolio risk in MVP theory is not sufficient to take account of this which leads to his disregard of this theory and methodology in the characterisation of diversity in the electricity system. It is with this in mind that this thesis applies Stirling's diversity heuristic in favour of MVP theory.

3.6 Chapter Conclusion

This chapter has introduced the concept of diversity drawn from a multi-disciplinary background. The quantification of diversity using various indices has been explored and the development of the Stirling Diversity Heuristic and its unique approach to tackling issues surrounding disparity discussed. In addition to quantifying diversity using these methods, an alternative, Mean-Variance Portfolio theory has also been considered with its drawbacks surrounding issues of ignorance and uncertainty considered against the alternative, the diversity heuristic provided by Stirling.

As well as the theoretical exploration of diversity, it has also been important to consider the importance of diversity in the context of the energy system. As seen throughout this chapter a wide range of academic disciplines have been drawn upon to discuss ideas and concepts of diversity and have applied these ideas in a number of ways. However, despite the centrality of diversity to economic theory and the many references to it in UK energy policy, particularly in relation to energy security, relatively few attempts have been made to develop the concept further and with this in mind, both of these multi-dimensional ideas which are somewhat ambiguous need further critical examination.

CHAPTER 4. Energy Systems Modelling

4.1 Chapter Introduction

This chapter introduces energy-economic modelling and more specifically MARKAL, the model used in this thesis. The chapter begins by introducing the different approaches to energy-economic modelling and then summarises the logic, structure and approach of MARKAL, including the details necessary to generate scenarios. The second part of the chapter discusses how MARKAL has been employed in recent years to inform UK energy policy as well as exploring the limitations of modelling in that regard.

4.2 An Introduction to Energy System Modelling

4.2.1 Scenario Analysis

Energy models are frequently used to generate scenarios for the future development of energy systems and to explore the impact of a range of assumptions on those scenarios as a way of exploring alternative future situations with a few to using them to inform and improve decisions that must be made despite uncertainty about the future (Hughes and Strachan, 2010).

There are a number of methodologies that have been used to generate scenarios across a number of disciplines; however, in the context of low carbon scenarios there are two dominant methodological approaches which can be used separately or in combination. The first of these involves building scenarios around high-level trends, derived from hypothesising a continuation and/or strengthening of an identifiable trend. The second approach is the concept of 'back-casting' which refers broadly to any approach that begins by defining and describing the desirable future and subsequently working backwards through time to identify respectively the various elements needed to bring that future about. This second approach has become increasingly employed to look at low carbon scenarios particularly with quantitative carbon emission targets, which provide a convenient end-point from which to begin.

As a result, this approach has become heavily associated with modelling studies²¹ driven by overall quantitative emission constraints such as those used in MARKAL (Hughes and Strachan, 2010, Hughes, 2009).

Scenario analysis in its various forms has been around since the 1950's and in the UK scenario analysis has been an important tool for informing energy policy for more than two decades. A number of models are in use, but for the purposes of this thesis the focus will be on MARKAL which has been used consistently for the last ten years to provide supporting evidence for Energy White Papers and other government documents such as the 2008 Climate Change Bill, the 2009 Low Carbon Transition Plan and on-going reports produced by the CCC. However, despite the reliance upon MARKAL, it is important to note that a range of models are used to provide insight into different policy related questions. Frequently, models are 'soft-linked' to enable their comparative strengths to be exploited (Strachan, 2011).

However, despite the importance of scenarios as a tool for informing energy policy, there are a number of limitations to this methodology. As discussed, quantitative scenario analysis relies upon formal mathematical models that are most appropriate for simulating well-understood systems over short periods of time. But as the complexity of the system increases and the time horizon lengthens, the applicability of such models diminishes. This is particularly relevant to a model such as MARKAL which includes over 6000 variables and represents a hugely complex system. In addition, the reliability of modelling depends upon accurate specification of the elements of the system, adequate understanding of the causal mechanisms and dynamics governing the system, the stability and persistence of those mechanisms over time and the ability to represent them mathematically with sufficient accuracy for simulation. These conditions are less likely to hold when assessing the long-range future of social systems, where state descriptions are uncertain, causal interactions are poorly understood and factors that are not quantifiable are significant (Swart et al., 2004). With these limitations of quantitative scenario analysis in mind it is important to consider this in the context of scenario generation for this thesis.

²¹ A modelling study generates scenarios which are the outputs of model runs and tend to focus on the whole energy system. Qualitative story lines can be used to explain or justify model results HUGHES, N. & STRACHAN, N. 2010. Methodological review of UK and International Low Carbon Scenarios. *Energy Policy*, 38, 6056-6065.

4.2.2 Energy System Analysis and Modelling

Energy modelling is used to support energy policy decisions and research. It specifically focuses on exploring future energy pathways concerning different energy technology choices and infrastructures in order to provide useful insights for policy. Energy systems lend themselves to this type of analysis because despite their complexity they are governed by relatively well-understood relationships. More specifically, this means that quantitative modelling is capable of representing the interactions between different elements of energy systems and capturing dynamics that are otherwise difficult to understand. Such modelling may be carried out at a number of different levels and scales varying from global to regional energy systems, down to individual industrial sites or houses.

For the purposes of this thesis, the energy system refers to the whole UK energy system with a supply side including energy resources e.g. conventional fossil fuels, renewable and advanced energy carriers such as hydrogen, energy processes e.g. oil refineries and infrastructure e.g. hydrogen import terminals and electricity and heat generation technologies e.g. CCS and end-use sectoral modules including residential, service, industrial, and agricultural and transport sectors, all of which include- all physical and policy constraints placed on the system.

Models come in many forms but for the purposes of this thesis the focus will be on the MARKet ALlocation (MARKAL) model which is a bottom-up, dynamic, linear programming (LP) optimisation model.

Models can be referred to as linear or non-linear according to their underlying equations, static or dynamic according to whether the model considers variations in time or not, deterministic or probabilistic according to whether 'chance' factors are considered and discrete or continuous according to the types of variables involved (Kapur, 1998).

In the literature, a distinction is commonly made between two types of model used to explore the relations between the energy system and the economy – namely '*bottom*

up' and *'top down*'. Conventional bottom up models are partial equilibrium representations of the energy sector and feature a large number of discrete energy technologies which capture the substitution of energy carriers on the primary and final energy level, process substitution and energy efficiency improvements (Bohringer and Rutherford, 2008) placing emphasis on the accurate description of the cost and performance of technology options, (Drouet et al., 2004). They often follow the assumption of perfect foresight (complete knowledge of the market of interest and its corresponding parameter's, both present and future) and are typically cast as optimisation problems computing the least cost combination of technologies to meet a given demand for final energy or energy services over a given time frame subject to technical restrictions and energy policy constraints (Bohringer and Rutherford, 2008).

Contrastingly, conventional top down modelling approaches adopt an economy-wide perspective focusing on the larger economic interactions and taking into account initial market distortions, pecuniary spill overs and income effects for certain economic agents such as households or governments. As a result the endogeneity of economic responses to policy shocks occurs at the expense of specific sectoral or technological details resulting in a limited representation of the energy system (Bohringer and Rutherford, 2008). Energy transformation processes in top down models are characterised by smooth production functions which are (the relationship between a sector's outputs and inputs) designed to simulate the potential substitutions between the main factors of production which are aggregated into just a few variables such as primary energy, capital and labour. This allows an economy to be represented by just a few variables and equations, with parameter values taken from the literature and derived by calibrating the model to a historical base year (Loulou et al., 2004).

This considerable simplification of *'top down models*' arising from the aggregation of variables in this way can lead to the neglect of specific technology options (particularly the introduction of new options) leading to the potential for such models to be *'technology poor*' and making it difficult to simulate key mechanisms such as technological change arising from rising fossil fuel prices (Loulou et al., 2004). A summary of the characteristics of *'top down*' down and *'bottom up*' models is provided in Table 4.

Table 4 – Summary of contrasting ‘top down’ and ‘bottom up’ model characteristics

‘Top Down’	‘Bottom up’
Adopt an ‘economic approach’	Adopt an ‘engineering approach’
Cannot explicitly represent technologies	Provide a detailed description of technologies
Reflect available technologies adopted by the market	Reflect technical potential
Use aggregated data for predicting	Use disaggregated data for exploratory purposes
Based on observed market behaviour	Independent of observed market behaviour
Tend to disregard the most technically efficient technologies which can lead to an underestimation of the potential for efficiency improvements	Disregard market thresholds (e.g. hidden costs) and so overestimate the possibility for efficiency improvements
Determine energy demand through aggregate economic indices such as GNP, but vary in addressing supply	Represents supply technologies in detail using disaggregated data, but vary in addressing supply
Endogenize behavioural relationships	Assess costs of technologies directly
Make the assumption of no discontinuity in historical trends	Assumes that interactions between the energy sector and other sector are negligible

Source: (Beeck, 1999)

Therefore in light of the limitations of both ‘bottom up’ and ‘top down’ models, three main types of ‘hybrid’ models have emerged. Firstly, the linking of independently developed ‘top down’ and ‘bottom up’ models, secondly, the focus on one model type in detail and the use of a ‘reduced form’ representation of the other and thirdly completely integrated models based on the development of sound algorithms for mixed complementarity problems which enable ‘true’ technology-based activity analysis in evaluating policy-induced structural change at the sectoral level (Bohringer, 1998, Bohringer and Rutherford, 2008, Schumcher and Sands, 2006, Rutherford, 1995, Dirske and Ferris, 1995). More simply, these are essentially top down models that also include bottom up modelling of selected parts of the energy system (Bohringer, 1998, Weyant, 1999). It is this third type of hybrid model to which MARKAL belongs; the focus of this thesis.

4.3 The UK MARKet ALlocation model (MARKAL)

4.3.1 Why MARKAL?

As we have seen, in the UK, scenario analysis has been an important tool for informing energy policy. The focus of this thesis will be on MARKAL because the important role it has played as a tool for informing UK energy policy. However, despite the focus on MARKAL, it is important to note that a range of models are necessary to provide policymakers with sufficient insight into a number of different policy related questions.

In fact, it is often possible to soft-link certain models to enable the strengths of different models to be exploited and allow benefits to be drawn from complementary analytical strengths (Strachan, 2011).

4.3.2 Linear Programming

MARKAL is considered a 'bottom-up' model based on linear optimisation (in the standard version) and minimises total system cost to meet exogenously defined levels of energy demand (i.e. energy demand from residential, service, transport industry and agricultural sectors). The model uses linear programming, a mathematical technique originally designed and used to plan the diversification of the US Air Force in 1947. This relies on linear equations, more specifically, linear inequations to represent the various relationships within the model. In MARKAL, as a linear optimization program, in its most simple form, the model chooses the best combination of energy technologies to satisfy demand.

A linear equation is a method of representing a relationship between two or more of the variables in the system which when plotted forms a straight line and can contain a selection of variables, coefficients and constraints. In the MARKAL model variables, coefficients and constraints are defined by the user as input data. A simple example of each of these entities in the model is as follows:

- Variable - the installed capacity of a coal-burning plant producing electricity.
- Coefficient - the investment cost per kWh of the coal-burning plant.
- Constraint - the maximum growth that can be expected in terms of installed capacity of such a plant during future decades.

A simplified linear inequation for the variable, coefficient and constraint shown above could state that *'the installed capacity of the coal burning power plant must be less than or equal to the maximum projected capacity in the future year'*.

A function of the variables, referred to as the objective function is minimised or maximised subject to the specific constraints of the model. In MARKAL, this is the total cost of the energy system over the entire time horizon (e.g. the period to 2050) which is minimised subject to limited resource supplies and other constraints.

The resulting solution to this linear program describes a set of technologies and energy flows that constitute an energy system that is both feasible within the constraints of the model (i.e. all numbers add up correctly in the model and all constraints set out are satisfied) and optimal (i.e. of all the possible solutions, the one displayed is the one that minimises total system cost) (IEA-ETSAP, 2004).

This example given above is a massive over-simplification of MARKAL because in reality the model contains more than 6,000 variables with a comparable number of equations. The model has thousands of technologies incorporated from all sectors of the energy system at the national level. Each technology is described by a number of technical and economic parameters and can be individually identified and distinguished (Loulou et al., 2004).

In the way described above, MARKAL computes a partial-equilibrium²² of energy markets. This means that the quantities and prices of fuels and other commodities are in equilibrium, thus the prices and quantities in each time period of the model are such that at those prices the suppliers produce exactly the quantities demanded by the consumers. In addition, this equilibrium has the property that the total surplus is maximized over the whole horizon. Investments made at any given period are optimal over the horizon as a whole (Loulou et al., 2004).

4.3.3 How does it work?

MARKAL is a 'bottom up' model capable of translating a set of assumptions about the costs of different technologies into 'cost optimized' (see section 4.3.2 for more details) solutions for the UK (Helm, 2003). It achieves this by choosing investment and operation levels of all the interconnected system elements that minimize the total system costs (MARKAL is a least cost-optimisation model). The UK MARKAL model is calibrated to within 1% of actual resource supplies, energy consumption, electricity output and installed technology capacity with the year 2000 as the base year. Agents are assumed to have perfect knowledge of future policy and economic developments. Thus, by manipulating input assumptions MARKAL is able to deliver outputs which

²² Partial equilibrium refers to a condition of economic equilibrium where only part of the market is taken into consideration, with all other things being held constant to attain equilibrium.

reflect an economy-wide solution of cost-optimal energy market development (Kannan, 2007).

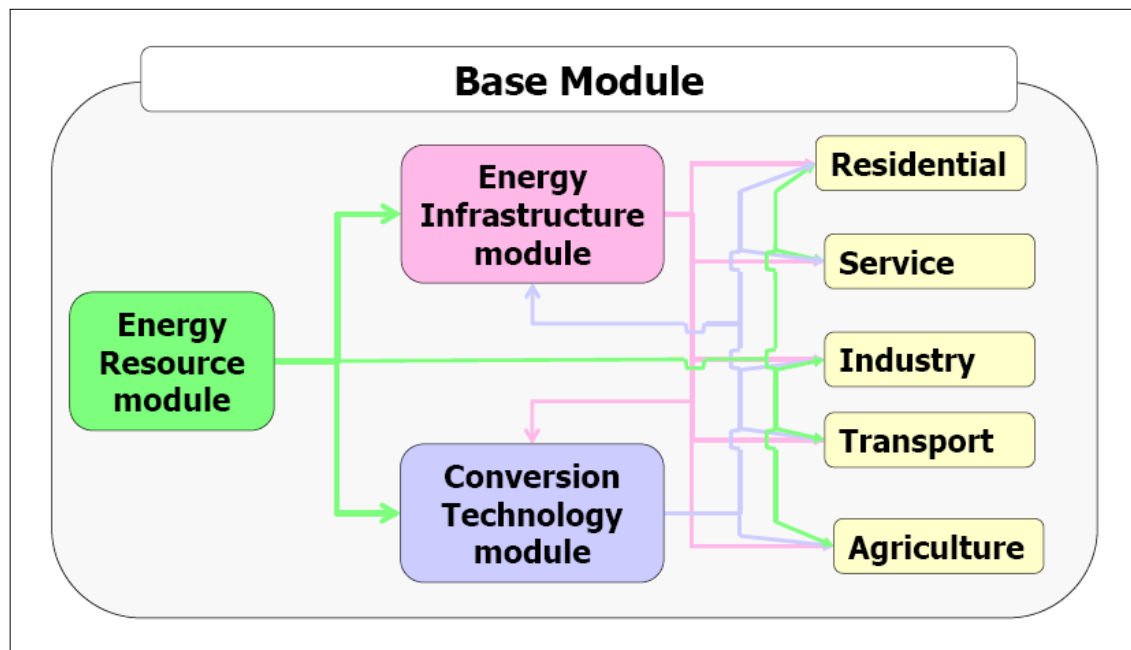
The UK model contains data regarding specific characteristics of the UK energy system such as energy resources and end-use technologies employed to meet demand. This enables detailed projections of the evolution of the UK energy system over time. The model was originally developed by the Brookhaven National Laboratory in the 1970s and is now supported by the IEA Energy Technology and Systems Analysis Program (ETSAP). In the UK, the UCL Energy Institute has been the main group responsible for the recent development of the model through the energy systems modelling theme of the UK Energy Research Centre (UKERC) for use in various research efforts to inform and support UK energy policy.

The model includes a number of physical and policy constraints in order to represent key physical, policy and regulatory aspects of the UK energy system (e.g. the implementation of taxes such as the carbon price floor and subsidies such as the UK Renewables Obligation). Thus enabling the implications of different policy options and constraints to be explored (Kannan, 2007, Strachan N, 2008).

4.3.4 Model structure

MARKAL is represented using a series of modules that can be classified as either supply or demand side (see Figure 11) and are described briefly below.

Figure 11 – Structure of the individual modules making up MARKAL



Source: (Kannan, 2007)

- Base module - is made up of all the energy carriers such as coal and oil and emission carriers such as CO₂ and SO₂.
- Energy resource module - contains all energy resource flows into the UK energy system (such as the extraction processes for fossil fuels and renewable energy supply).
- Energy Process and Infrastructure module - contains all the process technologies such as refineries and hydrogen production facilities and energy infrastructure such as gas transmission and distribution pipeline.
- Electricity and Heat (conversion) generation technologies module - contains all technologies responsible for electricity and heat generation as well as electricity transmission and distribution grids (Kannan, 2007).
- Residential – this module includes residential energy demand services and their corresponding end use technologies. There is no established UK data set for the residential sector. Therefore data for this module are calculated using reverse engineering from the base year 2000 using DUKES (2005). The sectoral level approach of MARKAL accounts for the aggregation of individual residential characteristics and attributes

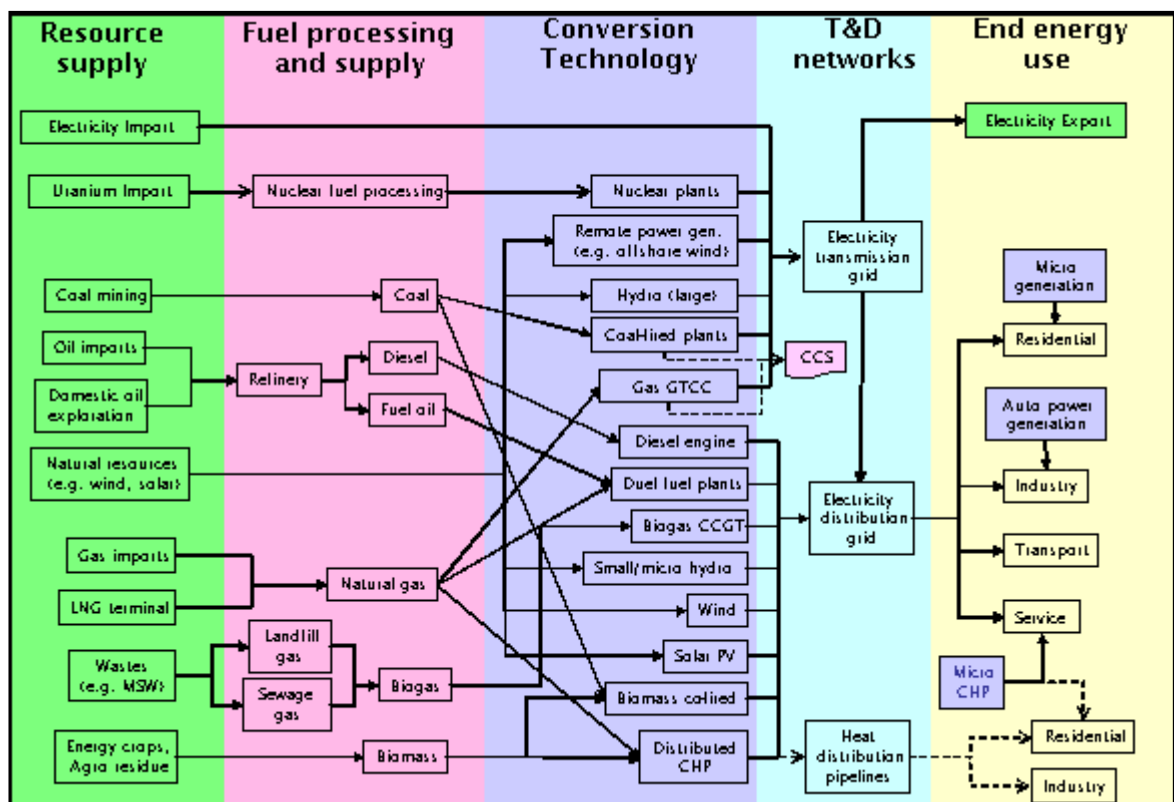
- Service – this module includes details of service sector energy service demands and their corresponding end-use technologies. The data for this module includes commercial, public administration and miscellaneous sectors and is aggregated due to the sectoral level approach of the model.
- Transport – this module includes details of transport energy service demands for various modes of transport and their corresponding end-use technologies. Energy service demand data for this module is taken from DUKES (2005) and vehicle input data from various UK government and industry reports (DfT, 2003, SA, 2005, IEA, 2005, JRC/CONCAWE/EUCAR, 2007). Fuel distribution networks used to track fuel are also included in this module.
- Industrial – this module consists of three layers of data made up of one layer of end-use demand and two technology layers; demand technologies and process technologies. MARKAL works by optimising these three layers together to meet energy demand from five energy service demands; iron and steel, non-ferrous metals, chemicals, paper pulp and publishing and other industries. The data for this module comes from the DTI, Future Energy Solutions (FES) and the Office for National Statistics.
- Agricultural – energy technologies in the agricultural sector are represented in the model at an aggregated level only due to the final energy demand of this sector being very low in comparison. It is possible to change energy use for this sector, as it is for other sectors in the model, through the Macro and MED versions of the model but this goes beyond the scope of this thesis (Anandarajah, 2009, Kannan, 2007).

4.3.5 The Reference Energy System

MARKAL portrays the entire energy system from resource supply including the import and domestic production of fuel resources through fuel processing and supply, explicit representation of infrastructure, conversion to secondary energy carriers (including electricity, heat and hydrogen), end-use technologies and energy service demands in the industrial, commercial, residential, transport and agricultural sectors (Kannan, 2007, Strachan N, 2008).

The 'reference energy system' (RES) is a network description of energy flows with a detailed description of all the technologies currently and potentially involved in the production, transformation and use of various energy forms. A simplified version of the RES is shown in Figure 12. From this it can be seen that in order to satisfy energy service demands, devices and technologies that transform energy carriers into useful energy are used. These are referred to as process technologies and conversion technologies. Process technologies produce storable energy carriers such as gasoline and diesel fuel and conversion technologies produce non-storable energy forms such as electricity and heat (Kannan, 2007).

Figure 12 – Reference Energy System for UK MARKAL



Source: (Kannan, 2007)

4.3.6 Different versions of MARKAL

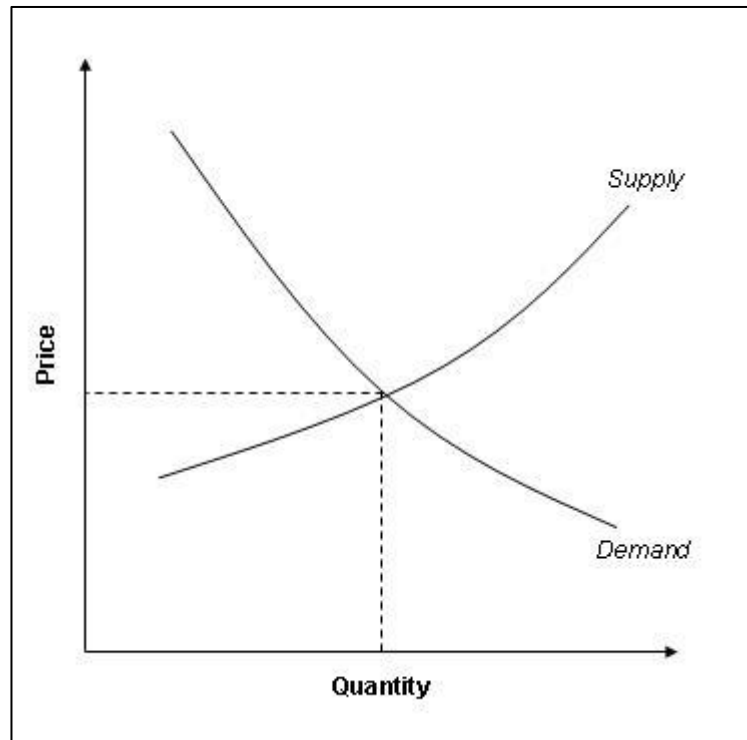
A number of variants of the MARKAL model have been developed. Variants enable certain limiting factors of the standard MARKAL model to be addressed and to allow alternate specifications and/or alternate functions to be used to answer specific research and policy questions.

The variant of interest to this thesis is the MARKAL-Elastic Demand (MED) because it accounts for the response of energy service demands to price by replacing exogenously defined energy service demands present in the standard version of MARKAL with demand curves which are implemented using a series of steps.

4.3.6.1 Deterministic MARKAL-Elastic Demand (MED)

The MARKAL-Elastic Demand (MED) variant was developed for the UK Energy Research Centre (UKERC) by the UCL Energy Institute in 2009. In the standard version of MARKAL energy demand is fixed whereas in the case of the MED variant, the energy service demands which are defined exogenously have been replaced with demand curves. These curves are calibrated to a reference case that matches the standard MARKAL reference case exactly, providing the MED variant of MARKAL with the option of increasing or decreasing energy demand as the final cost of energy falls and rises respectively. The MED variant, with the option of increasing or decreasing demands as energy costs rise and fall respectively can also be combined with supply responses to form alternate scenarios, for example low carbon scenarios where an emission constraint i.e. CO₂ is placed on the model (Anandarajah, 2009).

Figure 13 – Simplified representation of MED supply equilibrium



Source: adapted from (Anandarajah, 2009)

In the MED variant, demand functions are defined to determine how each energy service demand varies as a function of the market price of that energy service. Thus, each demand has a constant own-price elasticity (E) in a given period and is calculated as follows:

Equation 5

$$ES / ES_0 = (p / p_0)^E$$

Note - Where ES is a demand for some energy service, ES_0 is the demand in the reference case, p is the marginal price of each energy service demand, p_0 is the marginal price of each energy service demand in the reference case and E is the (negative) own-price elasticity of the demand (Anandarajah, 2009).

In this characterization, ES_0 and p_0 are obtained by running the standard MARKAL. ES_0 refers to the energy service demand projection which is defined by the user exogenously and p_0 is the marginal price of the energy service demand which is defined endogenously by running the reference case. A simple calibration process ensures that the reference case for the standard MARKAL, the MED variant and the undiscounted annual system cost align (Anandarajah, 2009).

In addition, three further parameters are required when using the MED version of the model:

1. MED-ELAST – elasticity of demand – this indicates how much energy service demands rises/falls in response to a unit change in the marginal cost of meeting the demands.
2. MED-VAR – variation of demand – this limits the upward/downward movement of demand response. In the UK model, this is set to a limit of 50% reduction in demand and a 25% increase in demand.
3. MED-STEP – defines the steps on the demand curve, for demand decreases, this has been set at a 2.5% reduction and 1.25% for demand increases (for consistency with the MED-VAR parameter).

A combination of the proportional change in prices and the elasticity parameter determines when the energy service demand changes by the step amount. It is important to note that the changes in energy service demand also depend on the availability and costs of technological conservation, efficiency and fuel switching options. The variation parameter sets the ultimate limit to the demand change and the step parameter determines the size of the increment in the model that can be selected for that variation. This does not mean that each demand response is log-linear but that the overall demand function is *not* log-linear as different demand steps are triggered by different price changes depending on the elasticities.

In contrast to the standard model, the objective function in MED is the sum of producer surplus and consumer surplus - commonly referred to as social surplus. In Figure 13, this is given by the area (in £) between the demand and supply curve between the origin and the equilibrium quantity. Social surplus will be affected by annualized investment costs, resource import and export and domestic production costs such as taxes, subsidies and emission costs - as is also the case in the standard MARKAL model. The MED variant is able to account for losses in social surplus, such as may arise from consumers reducing the quantity demanded due to higher prices.

In the scenarios generated using this variant of the model, transfers between producer and consumer surplus are possible. More specifically, if the policy case has higher

prices arising from an emission constraint then it is likely the producer surplus may take some of the consumer surplus; with the opposite occurring if the prices fall. The mechanism of this depends on the shape of the two curves and how the prices are passed through or not. In the higher price policy case, the combined surplus will always be lower. In a lower price policy case, the combined surplus will always be higher (Anandarajah, 2009).

4.3.7 Key Model Inputs, Assumptions and Limitations

MARKAL is a hugely complex model with far too many variables and constraints to discuss individually in detail. Therefore for the purposes of this thesis only those assumptions, constraints and variables of specific relevance will be discussed. These are summarised in the next section.

4.3.7.1 Global Discount Rate and Technology Specific Discount Rates²³

MARKAL uses a global discount rate that is used to discount all future costs (i.e. fuel, capital and all other plant costs) to a base year across the whole economy/energy system. Discounting is a technique used for comparing the costs and benefits that occur in different time periods and is based on the principle that people prefer to receive goods and services now rather than later and is a separate idea from inflation. This discount rate is used to convert all costs and benefits to ‘present values’ to enable comparison and is applied to public policy formulation where the aim is to take into account the needs of society as a whole over significant periods of time. The recommended social discount rate for long-term public policy analysis by the UK government is 3.5% and this is the value applied in MARKAL. (Treasury, 2010).

MARKAL also uses an ‘optional’ technology specific discount rate also referred to as the ‘hurdle rate’. This is because the energy sector has a large number of competing and frequently long-lived technologies, which are associated with different levels of risk. Therefore when assessing these technologies it is usually necessary to assess this risk and as result individual technology specific discount rates are based on this risk as opposed to simply applying the global discount rate to all technologies. This is particularly important when considering the private sector’s role in power generation

²³ Also referred to as Hurdle Rates in the literature

investment. Private sector discount rates are generally much higher than the social discount rate discussed above, as are the rates used historically by the state-owned power company in the UK. This is because in light of the higher risk, the private sector seeks higher rates of return hence higher hurdle rates are applied.

The ‘hurdle rates’ in MARKAL annualise capital costs using the ‘technology specific discount rate’. The investment cost of the technology is spread over its lifetime by applying a capital recover factor. The annualised investments and other costs such as operation and maintenance costs and fuel costs are then discounted to the present value. If no hurdle rate is applied, then the global discount factor is automatically used as the hurdle rate to annualise capital investment in MARKAL. If a hurdle rate is specified then the hurdle rate is used to annualise the capital. Thus the hurdle rate is applied only to annualise the capital investment. All other costs associated with the technology such as fuel are discounted using the global discount rate. Therefore the global discount factor is applied to the overall long-term annual discount rate for the whole economy, is used in the calculation of the capital recovery and is also used to report the discounted costs (i.e. total system cost) to a base year and enable any technology-based discount rate to be taken into consideration.

The technology specific discount rates in the MARKAL model for the power sector (and CCS electricity) are 10% and taken from the UK’s Green Book; the UK Government’s guidance of policy and evaluation (Treasury, 2010). However a review by Strachan (2008) of the study he suggests that the assumption of 10% hurdle rates in the electricity sector only is questionable. This is because the rationale of electricity being a competitive market versus other energy system sectors which require regulation is one justification. In addition, if hurdle rates are applied to the electricity sector then this raises questions as to whether they should be applied to other upstream energy chains or downstream technologies. Further discussion of this is outside the scope of this thesis, however it is important to note.

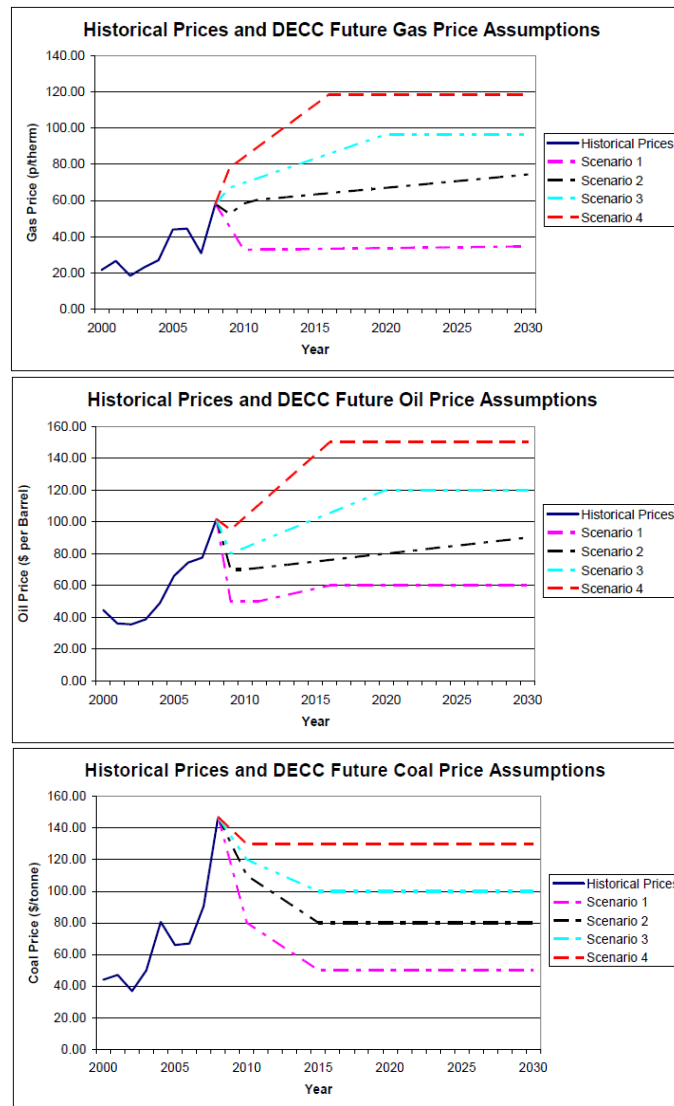
4.3.7.2 Resource Supply

All energy resources that flow into the UK energy system are incorporated into the model, of which there are almost 40. These include conventional fossil fuels such as

coal and gas, secondary fossil resources such as aviation fuel, renewable carriers such as wind and hydrogen carriers. Each of the resources in the model includes all the different sources of the resource; mining, import, exports and renewables with each node dealing with a single commodity. Each commodity has its own production cost and volume cost data which allows the generation of supply curves for each commodity. Each resource also details its cumulative resource availability, revenue from export and specifies bounds on its annual production (Anandarajah, 2009). Fossil fuel price assumptions can be varied in the model and for the purposes of this thesis the set of assumptions that are used are derived from DECC's long-term projections of the wholesale prices of oil, gas and coal for the UK up to 2030 (DECC, 2010a). The projections provided by DECC go up to 2030 however, for the purposes of the model these values are continued to 2050.

The DECC fossil fuel projections include four scenarios which provide a range of plausible futures and reflect long-term trends rather than short term-variability. They are summarised in the graphs below.

Figure 14 – Summary of DECC Fossil Fuel Price Projections



Source: (DECC, 2010a)

4.3.7.3 Demand

Energy service demands are represented in the model in six annual time slices, two diurnal slices (day and night) and three seasons (summer, winter and intermediate). Demand technologies that use electricity then the algorithm in the model calculates the electric demand capacity for each of the time period specified by the model by aggregating the demands in each period. As a result the model has two diurnal demands; day and night with significant daily variation (typically peak demand occurs for two hours in the evening) with additional seasonal variation to be considered and

the model's 'shoulder load'²⁵ occurs in the morning and last 5-6 hours. Due to such simplifications the model often underestimates actual load demands; a limitation of the structure of MARKAL (Anandarajah, 2009, Kannan, 2007).

Exogenous demand levels for energy services are derived from standard UK forecasts for residential buildings, transport, service sector and industry. On the whole, these sources involve low energy growth projections, with saturation effects featuring in key sectors. This reflects recent historical trends in economic growth and the reduction of the UK economy.

4.3.7.4 Technology Costs

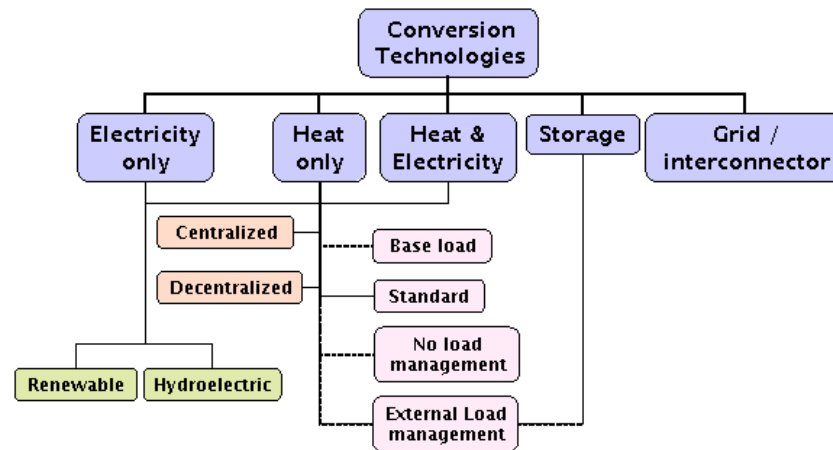
There are more than 100 power and heat generation technologies (conversion technologies) depicted in MARKAL. Each technology can be classified into one of four categories; electricity generating technologies, heat producing technologies, combined production heat and electricity generating technologies and storage technologies (see Figure 15). Each technology contains data for a set of parameters such as electrical efficiency, capital costs and availability factor. The use of individual parameters by the model is dependent on the structure of the model, calibration process and other physical, economic and structural constraints specified by the model (Anandarajah, 2009, Kannan, 2007)

Technology costs evolve over time and the data contributing to the parameters for each of the technologies depicted for the version of MARKAL used for this thesis are derived primarily from MottMacDonald (2010), MottMacDonald (2012) and ParsonsBrinckerhoff (2011).

Future technology costs in the model are based on expert assessments of technology vintages or for less mature technologies via exogenous learning curves which are derived from an assessment of historical learning rates combined with global forecasts of technology uptake.

²⁵Load refers to the electricity demand of the model/system and is often plotted over time as a load duration curve. The shoulder load refers to the peak in this load duration curve.

Figure 15 – Conversion technology characterisation



Source: (Anandarajah, 2009)

It is important to remember that like any model MARAL can only ever be as good as its data and input assumptions, including those surrounding future energy demands (discussed in the previous section) and the availability and costs of technologies. More specifically, MARKAL excludes key feedbacks (e.g. from the costs of technologies deployed which subsequently impacts energy prices or from the assumed level of CO₂ constraint to the cost of technologies) and since the choice of technologies is driven by cost minimization, marginal differences in assumed costs can ‘lead’ the model to choose one technology over another (a general feature of linear programming models such as MARKAL). In the ‘real-world’ there is often a greater continuum in the costs of technologies and in practice the costs of technologies can overlap leading to a range of technologies being deployed (DTI, 2003, DECC, 2003b).

Further limitations have been identified and commented on by Helm²⁶ (2003), a frequent critic of the MARKAL modelling. Helm suggests that the DTI White Paper does not provide sufficient evidence concerning the costs of renewable technologies and energy efficiency measures. In the absence of this data, the GDP claim made by the paper amounts to saying that ‘if the cost of renewables and energy efficiency is low then the effect on GDP will also be low’. As indicated in the White Paper, ‘bottom up’ models such as MARKAL:

²⁶ Dieter Helm is an Economics Professor at Oxford University and specialises in utilities, infrastructure, regulation and the environment and concentrates more specifically on the energy, water and communications sectors in Britain and Europe HELM, D. 2013. *Dieter Helm CBE* [Online]. Available: <http://www.dieterhelm.co.uk/> [Accessed 14/01/2013].

“...assume there is a lot of low or nil cost technology or energy efficiency potential. Estimates from such models can be criticised for under-estimating costs on the basis that they ignore various hidden costs, transaction costs or other constraints that in practice limit the take-up of what are, otherwise, cost-effective technologies” (Helm, 2003, DTI, 2003).

More simply, if certain costs are ignored then overall costs fall, making the modelled scenarios appear more favourable.

Helm identifies several categories of ‘ignored’ costs including transitional, network (to balance intermittent loads), feedback, informational, transaction costs and the impact of market pricing of risk on capital costs. He acknowledges that these costs are identified as caveats in the White Paper but also suggests that, despite this, conclusions are still drawn based on the MARKAL ‘predictions’. Helm also goes on to point out that the DTI claims that the MARKAL outcomes are in line with other similar European studies but in spite of this the interests of such studies arriving at their conclusions need further consideration. Particularly in reference to some of the market evidence available including the observed costs of renewables both built or under construction, the buy-out-price and the evidence for costs for renewables both *ex ante* and *post ante*.

4.3.7.5 Model Calibration

MARKAL is calibrated to base-year (2000) capital stocks and flows of energy. This enables the evolution of the energy system under different scenarios to be plausibly represented and an insight into different scenarios and their associated assumptions to be explored more thoroughly.

4.4 MARKAL and its application and relevance to UK Policy and Legislation

The MARKAL family of models have been used to provide analytical insights into the future of the UK electricity system for the 2003 and 2007 Energy White Papers, the 2008 Climate Change Bill, the 2009 Low Carbon Transition Plan and on-going reports of the CCC which are used to generate carbon budgets by DECC; most recently the 4th Carbon Budget. In each of these documents MARKAL has been used to address specific policy questions and the variant selected accordingly. This next section

explores each of these documents in detail and discusses how MARKAL has been used to answer specific policy related questions.

4.4.1 Summary of Energy White Papers

The MARKAL model was used to inform its first Energy White Paper in 2003 and since then has been subsequently developed as a tool to inform further White Papers as well as the CCC's 4th Carbon Budget.

The 2003 Energy White Paper used MARKAL to examine the cost of achieving a 60% reduction in CO₂ emissions by 2050 as recommended by the Royal Commission on Environmental Pollution (RCEP). The data from the Energy White Paper showed that the cost in meeting such an emission target was relatively low at 0.5-1% GDP in 2050. Further work was then commissioned to explore the drivers of this and other results were published in 2002 before the actual White Paper in 2003 (DECC, 2003b, DTI, 2003).

The second Energy White Paper published in 2007 used the MACRO variant of MARKAL (*MACRO-variant under a pre-determined economic growth path maximizes the discounted sum of utility derived from consumption*) to explore the technological and macroeconomic implications of reducing CO₂ emissions by 60% by 2050. This differs from the analysis in the 2003 Energy White Paper in such that the addition of the MACRO component allows long term costs of carbon abatement to be explored in detail. Thus, this enables the model to retain a large amount of technical detail regarding the entire energy system whilst explicitly calculating macroeconomic impacts out to 2050 (DTI, 2007).

The third White Paper to use MARKAL in 2009 sets out the UK's first comprehensive Low Carbon Transition Plan to 2020, which includes plans to reduce emissions by 18% by 2020 based on 2008 levels (a one third reduction based on 1990 levels), maintain secure energy supplies, maximise economic opportunities and protect the most vulnerable (DECC, 2009c). The reductions in emissions featured in this White Paper are based upon the UK's carbon budgets²⁷ which were set out in UK law in the 2009

²⁷ Carbon budgets are legally binding caps on greenhouse gas emissions that the UK produces over 5 year periods. The aim of these budgets is to chart using evidence the UK's pathway to an 80% reduction in emissions based on 1990 levels by 2050.

budget. The budgets indicate a significant role for renewables, CCS and nuclear, in achieving emission reductions as well as highlighting the importance of energy efficiency savings as a cost-effective method in meeting the 2050 target. This was put forward as the first measure to be taken in a move towards a low carbon economy.

4.4.2 UK Legislation

The Climate Change Act is the first legislation in the world to set a long-term legally binding framework to reduce carbon emissions. The Bill was introduced into Parliament on 14th November 2007 and became law on the 26th November 2008 and includes a target of an 80% reduction in GHG gases before 2050 based on 1990 levels. The two main aims of the Act are to improve carbon management to help in the UK's transition to a low-carbon economy and to demonstrate UK leadership internationally in an attempt to signal the UK's commitment to sharing its responsibility for global emissions (DECC, 2011b).

The Impact Assessment for the 2008 Climate Change Act used the MARKAL-MED variant to estimate long-term mitigation costs according to the 80% reduction in emissions based on 1990 levels by 2050; in line with CCC²⁸ advice. This variant of the model as opposed to those used in the 2003 and 2007 Energy White Papers enabled the incorporation of the flexibility of the UK to meet some of its long term targets through international trading. However this assessment uses the MARKAL data and modelling from the 2003 and 2007 Energy White Papers for context and reference.

Energy models have been used consistently by the CCC and the government to provide an evidence base for policy and most recently was used to inform the 4th Carbon Budget which covers the period 2023-2027 in late 2010 (Usher and Strachan, 2010). The focus of this study was the associated uncertainties in the feasibility and costs and trade-offs of alternate pathways to 2050. More stringent reductions in CO₂ emissions were used and so were extended to a 90% and a 95% reduction by 2050 to recognise the uncertainty in the contribution of non-CO₂ GHG emissions, emissions from land-

Commitments in the first three periods of the budget were a reduction of 22% in the first period from 2008-12, a 28% reduction in the period to 2013-17 and a 34% reduction in the period to 2018-22 DECC 2009b. The Low Carbon Transition Plan: Analytical Annex. London: Department of Energy and Climate Change.

²⁸ The CCC is an independent agency set up under the Climate Change Act to advise the government on setting and meeting carbon budgets and on preparing for the impacts of climate change CCC. 2012. *CCC Home* [Online]. Committee on Climate Change. [Accessed 15/10/2012].

use change and emissions from international bunker fuels (heavy petroleum products such as diesel).

4.5 Chapter Conclusion

This chapter has introduced Energy Systems Analysis and Modelling and provided a detailed introduction to the MARKAL model, the model of interest to this thesis, selected because of its use to inform UK energy policy over the past decade. The origins, underlying structural assumptions and various limitations of the model are described in relation to generating scenarios suitable for this thesis and the White Papers which MARKAL has been used to inform have been touched on briefly.

The next chapter, chapter 5 introduces the research design and methodologies for this thesis. More specifically this chapter will introduce the research questions and the context for asking these questions along with providing a framework of the necessary theoretical and methodological tools necessary to answer these questions.

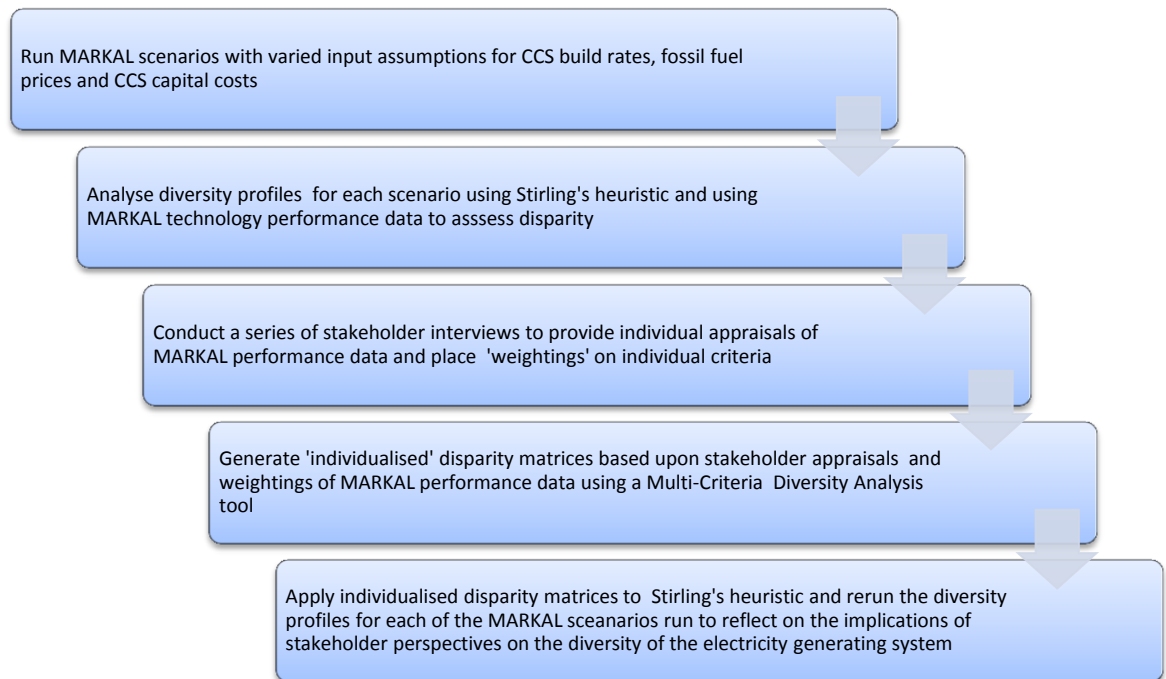
CHAPTER 5. Research Design and Methodologies

5.1 Chapter Introduction

The aim of this chapter is to present the research questions for this thesis and introduce the methodological tools necessary to address these. The review of the literature on CCS, diversity and energy systems modelling was summarised in Chapters 2, 3 and 4 respectively. More specifically, Chapter 3 highlighted the need for further work on the quantification of disparity which until very recently was neglected in the literature whilst Chapter 4 introduced the energy-economic model MARKAL which can be used to generate scenarios of policy relevance to the UK Electricity System to 2050. This provides a basis for the investigation of the diversity of the UK electricity system and the contribution of CCS to that diversity; both topics of considerable interest to the UK power sector and UK energy and climate change policy.

The methodology developed for answering these questions incorporates both quantitative and qualitative techniques. More specifically, this thesis uses MARKAL, a model selected due to the central role it has played in informing UK energy policy, to generate a set of scenarios with varied assumptions. Scenarios were then analysed to generate a diversity profile which used the Multi-Criteria Diversity Analysis (MDA) tool (see Chapters 6 and 7) to generate disparity matrices of the technologies found in MARKAL which were then in turn used to calculate the diversity of the different data points (five yearly increments between the year 2000 and 2050) in each scenario. This was then followed by a series of Stakeholder Interviews which enabled individual stakeholders to conduct an appraisal of the technology performance data in MARKAL which can be subsequently used to generate a personalised disparity matrix accordingly, once again using the MDA tool. Each actor's disparity matrix was then inputted into a template and the diversity profiles of each scenario run to incorporate this data and to enable an investigation into whether this has an effect on the diversity of scenarios generated using MARKAL. This is represented as a flow chart in Figure 16.

Figure 16 – Flow chart illustrating the ordering of thesis methodologies



5.2 Research Questions and Thesis Aims

The aim of this thesis is to study the concept of diversity and the implications that CCS technologies could have on the diversity of the UK electricity system. As discussed in Chapter 2 CCS technologies are being developed to help reduce carbon emissions and allow the UK to meet its legally binding carbon reduction target of 80% by 2050 (based on 1990 levels). They are also expected to increase the diversity of the UK generating system by allowing the continued use of fossil fuels. The concept of diversity has been referred to in UK Energy Policy since the 1940's, however there has been little attempt to clarify this concept or formalise this or indeed explore the implications that diversity could have on the UK electricity system as we saw in Chapter 3.

As a result, this research has been designed to address the following question '*What impact could the deployment of Carbon, Capture and Storage technologies have on the diversity of the future UK electricity system?*' It uses MARKAL and a Multi-Criteria Diversity Analysis tool together to explore electricity system diversity and in so doing, contribute to the modelling literature, the diversity literature and the UK energy policy literature.

In the context of the UK energy system and adhering to the fact that CCS is not yet a commercially viable technology it seems reasonable to break down this question into three more manageable questions.

1. *What are the potential effects of the deployment of Carbon, Capture and Storage technologies on the diversity of the UK electricity system between now and 2050?*
2. *How are key variables and constraints likely to influence the deployment of CCS and what impact could these have on the diversity of the UK electricity system?*
3. *How does the relative emphasis stakeholders place on the various aspects of technology performance affect their appraisal of electricity system diversity in different scenarios?*

The first of these questions is addressed by creating two reference scenarios; one run with the deployment of CCS technologies and one without the deployment of CCS technologies (achieved by placing a constraint on the model so that it is unable to deploy CCS technologies). The diversity profiles of the subsequently generated scenarios can then be compared to look at the effect of introducing CCS technologies on diversity.

The second of these questions is addressed by manipulating key variables and constraints in the MARKAL model, which may influence the deployment of CCS technologies and using these to produce a series of scenarios and estimating the diversity of each scenario. The variables of interest are the maximum rate of investment in CCS technologies ('CCS build rates'), the capital costs of CCS technologies and fossil fuel prices.

The final question is addressed by interviewing key stakeholders in the CCS debate to appraise the data and assumptions about technology performance within the MARKAL model. Their responses are then inputted into a Multi-criteria Diversity Analysis tool to generate 'personalised' disparity matrices, which are then used to re-estimate the diversity of each scenario. These can then be compared between stakeholders to assess the implications of stakeholder perspectives on diversity. This in combination with the other results generated in this thesis can then be reflected on to consider the overall implication of that they have on diversity.

5.3 Methods of Data Collection and Analysis

This section will focus specifically on the methodologies used in this thesis by building on Chapter 4 to discuss the specific variables and constraints this thesis has applied to the model to generate scenarios. It will then go onto introduce the multi-criteria diversity analysis tool for this thesis in more detail and the interview process for stakeholders.

5.3.1 MARKAL Scenario Generation

The MARKAL model has over 6,000 variables and 1,000 constraints so therefore it is impossible to explore all of these individually in this thesis. As discussed earlier in this thesis, CCS is as yet a commercially unproven technology; therefore there is no operational data for CCS from which to draw upon in order to help us to explore its future deployment. As a result, there is a large amount of uncertainty surrounding CCS technologies and so it is important to select variables for this thesis that enable certain uncertainties to be explored in more detail and more specifically, how they can affect the contribution of CCS technologies in MARKAL model runs.

The literature identifies seven key uncertainties about the future development of CCS and it is from this that the variables for this thesis have been selected. These seven uncertainties include; which CCS pathway to pursue due to the array of technological diversity being developed, whether storage of CO₂ over long periods of time is safe, is the scaling-up and speed of development and deployment needed possible, how will CCS be integrated into existing systems, what is the future economic and financial viability of the technology for investors, what policies, political and regulatory landscapes need to be in place and finally are CCS technologies publically accepted (Markusson et al., 2010). However despite its complexity it is not possible to explore each of these uncertainties using MARKAL. MARKAL can be used to explore three of these uncertainties; the maximum rate of investment in CCS technologies (referred to later in this thesis as 'CCS build rates'), the capital costs of CCS technologies and fossil fuel prices.

Further constraints applicable to the scenarios generated will also be discussed in further detail in the proceeding sections. This will first begin by a discussion of the reference scenarios and its assumptions and constraints applicable to this thesis.

5.3.1.1 The Reference Scenario

The reference scenario is used as a baseline to which all other scenarios generated in this thesis are compared. In this thesis, two reference scenarios will be run, one with the option for the model to deploy CCS technologies and one without the option for the model to deploy CCS technologies. The creation of two such scenarios will enable the first research question to be answered by enabling a comparison of the effects of the deployment of CCS technologies on the diversity of the electricity system to 2050. However, only the reference scenario with CCS deployed will be used for comparison with other scenarios generated for this thesis.

As discussed in Chapter 4, a scenario is constructed using a set of input assumptions and constraints within a series of modules. The key assumptions and constraints for the reference scenario are outlined in Table 5 and are in part inherited from the modelling work carried out by UCL for the CCC's 4th Carbon Budget.

Table 5 – Key assumptions and constraints for the Reference Scenario

Parameter	Assumptions
Emission Constraint	Baseline CO ₂ emissions to 2010 based on current figures, 80% reduction in CO ₂ emissions by 2050 based on 1990 levels, DECC Carbon Targets to 2020
Hurdle Rate Constraint	10% for power generation technologies
CCS Constraints	Industrial CCS incorporated, 425MW capacity of CCS to be in place by 2015, CCS plants built are in operation at least 50% of the time for the next 10 years and at least 33% of the time in the following 10 years, from this point onwards the model is then free to choose whether to use these technologies or not. ²⁹
Policy Constraints	A number of policies are modelled including the Renewables Obligation included, the Carbon Price Floor, Feed in tariff's for solar PV, micro-CHP, micro-hydro and wind, DECC Carbon Targets to 2020
Fuel Price Constraints	DECC Central Fuel Price Assumptions (see 6.2.3 for more details)
Energy Demand Constraints	BERR ³⁰ Energy Demand Model assumptions

5.3.1.1.1 Emission Constraint

An emissions constraint is implemented in all of the scenarios generated. This ensures that each scenario meets the UK's 80% greenhouse gas reduction target (as noted in the CCC (2008) an overall target of an 80% reduction in GHG may also mean a reduction in UK energy system CO₂ emissions closer to 90% depending on assumptions made on the long-term path of emissions from aviation, shipping and non-CO₂ GHG emissions) by 2050 as set out by DECC's Carbon Plan (2011a) as well as an interim carbon target for 2020, which indicates that carbon emissions are to be reduced by a third by 2020, based on 1990 emission levels. Within these constraints, actual historical emission figures to 2010 are included and then beyond 2010 the model is free to choose according to other assumptions and constraints, the emission pathway to 2050.

²⁹ Industrial CCS assumptions are taken from the Element Energy (2010) report and provided for the purposes of this report by the CCC based on their earlier modelling work. Analysis of these assumptions (which translate into those above) support CCS having the potential to address up to 38Mt of CO₂ emissions per annum in 2030 at costs between £30-150 per tonne of CO₂ abated. This assumes that the capital costs of capture plants is discounted at a rate of 10% over twenty years and that some clustering of sources occurs for transport and storage. It also assumes government projections of 'central' energy prices. The CCC requested these figures be used again by UCL in the modelling work for the CCC's 4th Carbon Budget based on the strength of their analysis with no evidence arising that would suggest that these numbers should be revised.

³⁰ BERR was the UK Department for Business, Enterprise and Regulatory Reform which was replaced by the Department for Business, Innovation and Skills (BIS) in 2009.

5.3.1.1.2 Hurdle Rate Constraints

The hurdle rates implemented in the reference scenario for the power sector are 10% for all generation technologies. Detail on hurdle rates can be found in 4.3.7.1. where a critique for the 10% hurdle rate can also be found.

5.3.1.1.3 CCS constraints

As explored in earlier chapters, CCS has not yet been proven as a commercially viable technology. As a result there is no empirical data from actual plant operation to input into the model and use as a basis for this technology and so a number of assumptions are required for its incorporation into the model. Several CCS constraints are incorporated into the reference module as follows:

- A 425MW of capacity of CCS is forced into the model by 2015 (to represent an initial UK demonstration project), and CCS plants subsequently built in the model are in operation at least 50% of the time for the next 10 years and at least 33% of the time in the following 10 years. This ensures that there is some activity in the model from this set of technologies. After this point onwards the model is then free to choose whether to use these technologies according to other assumptions and constraints in the model.
- In the reference scenario the maximum annual rate of investment CCS technologies (i.e. CCS build rates) are constrained to 0.5GW per annum from 2010 which then rise to 1GW per annum from 2025, 1.5GW per annum from 2030 and from 2035 2GW per annum thereafter. This set of build rates were agreed by the Committee on Climate Change during a stakeholder workshop set up to discuss the constraints surrounding MARKAL before running scenarios which were used to inform the 4th Carbon Budget (see section 5.3.1.3.1 for critique).

5.3.1.1.4 Fossil Fuel Price Constraints

The fossil fuel prices for the scenarios in this thesis are taken from a study by DECC (2011c) which is an update of earlier assumptions published by DECC in 2008 (the year DECC was established and the point from which it ran the energy model). The methodology used to generate these assumptions combines three approaches; the global supply demand framework, surveying price forecasts from international

organisations and industry players and using information on the long run marginal cost of fuels.

These assumptions are used for government analysis of policy options which affect both the demand and supply of energy to the UK. The assumptions draw on the best information available concerning market fundamentals and feedback received assumptions used in previous studies. More specifically and very importantly the volatility seen in the recent global financial crisis has led to high degree of uncertainty about fossil fuel prices which has also been captured in the four scenarios created and the values for each are summarized in Figure 14 and a visual representation of these figures can be found in Table 6. A critique of these scenarios can be found in 4.3.7.2. However, it is worth re-iterating at this point that forecasting fuel prices is very difficult, no matter how comprehensive such forecasts aim to be. Thus, it is important to remember that the aim of this thesis is to test the range of possible impacts of variables such as fossil fuel prices on CCS deployment and diversity rather than being an exercise in predicting the future.

Table 6 – Central Fossil Fuel Price Assumptions from DECC

	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
Oil	4.12	9.35	6.41	6.87	7.33	7.79	8.25	8.25	8.25	8.25	8.25
Gas	1.93	4.47	4.47	4.85	5.16	5.47	5.7	5.7	5.7	5.7	5.7
Coal	0.91	2.97	2.23	1.62	1.62	1.62	1.62	1.62	1.62	1.62	1.62

Note – units 2000£/GJ

5.3.1.1.5 Policy Assumptions and Constraints

While this thesis is not specifically focused on the government policies incorporated into the MARKAL model these policies are an important part of the model which has significant influence on scenario outputs.

There are several policies incorporated into the model which represent the policy mix in the UK. These include the Renewables Obligation, DECC Carbon Plan Targets, the Electricity Market Reform (including the introduction of the Carbon Price Floor and various feed in tariffs).

The Renewables Obligation (RO), introduced in 2002 and administered by Ofgem, is the main financial mechanism that the Government uses to incentivise the deployment

of large-scale renewable electricity generation and thereby to comply with the UK's obligations under the EU Renewables Directive. To date the mechanism has supported the deployment of increasing amounts of renewable capacity from 3.1GW in 2002 to 13GW in the first quarter of 2012 which has increased the share of renewables in electricity generation from 1.8% at the start of the RO to 10.3% in 2012 (excluding hydro technologies). To further strengthen investor confidence the end date of the scheme was extended in 2010 to 2037 from 2027 of new projects and to continue to ensure the deployment of renewable technologies in the pursuit of the UK's 2020 target and beyond (DECC, 2012f, DUKES, 2013). Further details of the RO and its development between 2002 and 2010 can be found at (Mitchell and Woodman, 2011).

In the model the implementation of the RO is such that all generation technologies covered by the RO are constrained to a minimum of 15% of total electricity generation by 2015, 30% in 2020 and 40% from 2030 onwards in line with current renewables targets.

Running alongside the RO in the UK and also incorporated into the MARKAL model are a number of Feed in Tariffs (FITs). The aim of DECC through the use of FITs (introduced on 1st April 2010) is to encourage the deployment of additional small-scale (<5MW) renewable electricity generation by those parties such as businesses, communities and individuals that have not traditionally been engaged in the electricity market. The purpose of the scheme is too allow people to invest in small-scale low-carbon electricity in return for a guaranteed payment from an electricity supplier (of their choice) for the electricity they generate in addition to a guaranteed payment for unused surplus electricity they export back to the grid. The technologies eligible for FITs are solar photovoltaics (PV), wind, hydro, anaerobic digestion and domestic scale micro-CHP (<2KW capacity).

The Electricity Market Reform (EMR) is being designed to secure the investment necessary to deliver a reliable, diverse and low carbon technology mix in the future. The long term vision of the EMR is to *'create a market under which low carbon generators are able to compete fairly under a carbon price that is both stable and robust'* (DECC, 2012c). Due to the fact that many low carbon technologies are still at

different stages in their development this vision still remains at least 15 years away. The purpose of the EMR is to provide a process and mechanism under which this long term transition with three prime objectives, to ensure the security of supply, to ensure sufficient investment in sustainable low carbon generation and to maximise benefits whilst minimising the costs to the whole of the economy (DECC, 2012c).

The implementation of the EMR involves two new market mechanisms; feed-in tariffs with Contracts for Difference (CfDs) which are long term contracts which provide revenue certainty to investors in low carbon generation such as CCS-equipped plants, renewables and nuclear generation as well as 'capacity mechanisms' which are payments for reliable capacity to be available when needed to help ensure the security of supply. Support to these mechanisms will be provided by the introduction of a Carbon Price Floor and an Emissions Performance Standard, both incorporated into the two reference runs in MARKAL (DECC, 2012c).

Feed in tariffs have already been discussed but the other supporting market mechanism, the Contracts for Difference will operate by facilitating investment in low carbon generation (including CCS plants) through removing long-term exposure to electricity price volatility by stabilising returns for generators at a fixed level referred to as the strike price. Generators benefit by receiving revenue from selling their electricity into the market, but when the market price of electricity is below the strike price they will also receive a top-up payment from suppliers for the additional amount. If the converse situation occurs and the market price of electricity rises above the strike price then generators must pay back the difference. This mechanism should enable low carbon generators to be active participants in the wholesale electricity market (DECC, 2012c). This mechanism however, is not yet built into the model which requires consideration in the subsequent analysis of scenarios later in this thesis.

One of the two supportive mechanisms, the DECC Carbon Price Floor (CPF) was announced by the Chancellor in the 2011 budget, introduced into the Finance Bill 2012 and is due to come into effect on the 1st April 2013 and has been introduced into the model. The basis of this policy is to provide a clear economic signal to move away from high-carbon technologies such as unabated fossil fuels by increasing the price

paid for emitting the associated carbon. By implementing this policy, a value is placed on the price of carbon of ~£16/tCO₂ in 2013 (according to 2009 prices), which is set to rise to £30/tCO₂ by 2020 (according to 2009 prices) (Davey, 2012). The CPF of £30/tCO₂ is expected to drive between £30 and £40 billion of new investment in low carbon and increasing low carbon generation capacity by 7.5-9.3GW by 2030 (HMRC, 2011).

The other supportive mechanism to the CfDs and the feed in tariffs is the Emissions Performance Standard (EPS) which is a regulatory measure to provide a back-stop to limit emissions from unabated power stations. In addition to the CfDs the EPS is also not yet built into the model. The absence of these two constraints in the model provides several limitations. In the first instance, the CfDs are available for CCS developers/generators and so the absence of this in the model may reduce the capacity of CCS built. This is because the aim of the CfD is to remove electricity price volatility and subsequently facilitate investment in low carbon generation technologies. With regard to the EPS, this regulatory mechanism is aimed at new unabated power stations and not existing stations which has proved controversial and the subject of much debate in Parliament as part of the Energy Bill scrutiny.

5.3.1.2 Energy Demand

The DECC³¹ Energy Demand Model is used to inform the demand side of MARKAL. This model is a partial equilibrium model of the UK energy market comprising an integrated demand sector and an electricity supply sector. The demand sector of the model is an econometric-time series model and the supply side is a least cost optimising model of electricity generating plants.

The basis for the econometric-time series model are historical relationships which are assumed in this instance to continue relatively unchanged into the future and so the further into the future that the demand model is used to forecast then the greater the uncertainty surrounding the scenarios due to the increased problematic nature of this assumption.

³¹ BERR refers to the Department for Business, Enterprise and Regulatory Reform which is now called the Department for Business, Innovation and Skills (BIS).

The approach of the DECC Energy Demand Model is to look separately at demand for fuel for different sub-sectors of the economy; transport, industry, domestic and other. Fuel can be disaggregated into the following categories; oil, gas, electricity, solid fuels, renewables and heat. These two sets of categorisations are based on DUKES³² classifications.

5.3.1.3 Thesis Scenarios

We have discussed the various assumptions and constraints for the reference scenario. Further to the reference scenario, 10 more scenarios were generated which varied further the CCS build rate constraints, fossil fuel prices and CCS capital costs. As discussed previously these scenarios are designed to reflect the very wide range of uncertainty for each of these variables. This in turn may be expected to have a major influence upon the level and rate of CCS investment, the subsequent utilisation of CCS plant and hence the overall diversity of the UK electricity system.

5.3.1.3.1 CCS Build Rates

The maximum rate of investment in CCS technologies (i.e. CCS build rates) refers to the capacity of CCS technologies that can be deployed in a given time period. It is considered in 5-year increments and is applied to all major generation technologies in the model. Exploring this variable in more detail will help to determine whether targets for CCS such as 10GW of fossil fuel generation with CCS by 2030 set out by the Carbon Plan or the industry ambition for 20-30 GW of CCS technology capacity by 2030 are actually achievable.

Therefore it is important when formulating different ‘CCS build rate’ assumptions to take into consideration both historical build rates in the UK and the physical limitations on technology deployment. Historical build rates in the UK peaked during the ‘*dash for gas*’ in the 1990’s in which an average of 2.5GW annual increase in capacity was achieved. However, this rate of deployment was exceptional, with the average rate of deployment in the 60s, 70s and 80s not exceeding that of 0.5GW per annum (Usher and Strachan, 2010). It is important to acknowledge that both of these figures quoted are average figures and there will be some years during each of these timeframes

³² DUKES – Digest of UK Energy Statistics

when build rates would have exceeded the averages. However, they do provide a useful starting point when considering the build rates to implement for this thesis and they raise question as to whether increasing CCS build rates above 2.5GW per annum is actually feasible. Thus, the fact that 2.5GW is historically the maximum level of deployment achieved for power generation in a single year provides a good rationale for setting 2.5GW deployment of CCS per annum as the upper limit for deployment in the high-high scenario. It is important to note that analysis arising from scenarios using this maximum deployment capacity should be considered carefully and the uncertainty surrounding whether similar deployment rates could once again be achieved reflected upon.

Similarly, when constructing build rate scenarios at the other end of the spectrum and considering the lowest level of CCS deployment rates it important to consider that 0.5GW deployment per annum was the average deployment across three decades. In addition to possible limitations on the deployment of technologies it is also important to consider the fact that first generation CCS technologies range between 200MW and 400MW in size. Furthermore, the CCS Cost Reduction Task Force (CRTF, 2013) suggests that early phase plants should be 600MW to 800MW in size to help reduce the levelised cost of electricity from these plants and they also acknowledge that projects over 1000MW should also be considered at this stage. This is particularly important when considering economies of scale, which are captured, by scaling up the size or the number of units (a project specific choice). The scaling up of plants is particularly significant in achieving reductions in electricity costs and the CRTF suggest that this will be achieved by scaling up plant sizes to 1GW or more; the equivalent of unabated plants being installed globally today. Generally speaking, the scaling up of plants will contribute to lowering plant capital costs; however, there is nothing in the literature to suggest a minimum capacity for deployment indicative of reducing capital costs as indicated or to sustain the industry. Therefore taking into consideration average historical build rates and the size of first generation technologies, the deployment of CCS technologies of 0.5GW per annum is put forward for the reference build rate scenario.

In addition to considering the physical constraints for deployment it is also important to consider previous modelling and policy studies and see how this compares with the proposed deployment rates for this thesis. There are a number of publications and policy documents³³ that set targets for the deployment of CCS technologies and that have made use of MARKAL scenarios. Here, we shall consider briefly the analysis for the carbon budgets produced by the CCC and the Carbon Plan. It is important to note when considering each of the documents below that the MARKAL scenario runs considered have many varying assumptions and constraints and do not address the same questions asked in this thesis, however, they are useful to refer to the different levels of investment in CCS considered and subsequently the ‘build rates’ utilised.

The first three carbon budgets were set out by the CCC in ‘Building a low-carbon economy – the UK’s contribution to tackling climate change, published in December 2008 and providing the CCC’s recommendations on the 2050 emissions reduction target and advising on the levels of the UK’s first legally binding carbon budgets for 2008-2022. MARKAL runs were completed by UCL (as part of UKERC) in conjunction with the AEA Technology and the Policy Studies Institute and focused on an assessment of different 2020 and 2050 emission targets, ranging from 60-95% CO₂ reductions in 2050. A range of variants were implemented to explore the contribution of international carbon credits, the impact of short term goals on the ability of the system to meet longer term goals, the role of key low carbon technologies in meeting long term abatement goals and short term renewable targets of 40% of electricity generation. The CCS build rates used to explore this range of issues were varied between 3-5GW per annum post 2020. At maximal deployment this would equate to between 30-50GW of CCS technologies by 2050.

The fourth carbon budget analysis (period 2023-2027) was published by the CCC in 2010. MARKAL runs were once again completed by UCL as part of UKERC and incorporated more stringent CO₂ emission reductions in 2050 of 90% and 95%. These more stringent emission targets were examined in this modelling exercise to reflect

³³ MARKAL was also used to inform the 2003 and 2007 Energy White Papers and the Climate Change Bill 2008, however, these utilised the standard version of MARKAL, not the MED-version used in this thesis, therefore the documents referred to only include those using the MED-version of the model.

additional efforts in abating UK energy CO₂ emissions and recognises the uncertainties in the contribution of non-CO₂ GHGs, emissions from land use change and emissions from international bunker fuels. Furthermore, this exercise included considerable updates to the model in addition to the development of a stochastic version³⁴ of the model. The CCS build rates implemented are set out in Table 7. If deployed at the maximal rates then by 2030 10GW of CCS capacity could be expected.

Table 7 – Build rates implemented in the MARKAL scenario runs for the 4th Carbon Budget.

	2015	2020	2025	2030	2035+
GW per 5 year time period	2.5	2.5	5.0	7.5	10

The Carbon Plan set out in 2011, suggests that 40-70GW of new low carbon electricity generation is needed by 2030 and that CCS could contribute as much as 10GW. The Carbon Plan set out the government's plans for achieving the emission reductions it has committed too including the different actions and milestones. Evidence from the CCC analyses of the carbon budgets was used by the government to inform the Carbon Plan but is it important to highlight that the analysis by the CCC was independent.

The Carbon Plan suggests a capacity of around 10GW of CCS is needed by 2030 and the later published DECC 'CCS Roadmap' (2012) suggests a much higher figure of 20-30GW. In addition to the physical constraints for CCS technology deployment discussed earlier, it is also interesting to consider how the build rates / assumptions contrast with the policy documents highlighted here. The reference scenario which demonstrates the lowest level of investment in CCS technologies for this thesis, would allow up to 10GW capacity to be deployed by 2030, aligning with the government's plans set out in the Carbon Plan. The central build rate scenario which doubles the build rate of the reference scenario, would allow 15GW of CCS to be deployed by 2030.

³⁴ Stochastic MARKAL varies from the MED version of the model in such that it relaxes the assumption of forward looking model solutions and uses a two stage stochastic decision based on expected cost, where key parameters are made explicitly uncertain and in the first stage of the model the model is able to pursue hedging strategies beased on the weighted costs of future uncertain outcomes. In the second stage of the model the model is able to give multiple recourse strategies as the model reacts to different outcomes of the uncertain variable. This creates insights into the optimal evolution of the UK energy-economic system under considerations of uncertainty and the expected value of perfect information can also be calculated USHER, W. & STRACHAN, N. 2010. UK MARKAL Modelling - Examining Decarbonisation Pathways in the 2020s on the Way to Meeting the 2050 Emissions Target. UCL.

The high scenario triples the deployment of CCS and enables up to 22.5GW of CCS capacity and finally the high-high scenario quadruples the reference scenario deployment of CCS technologies enabling up to 30GW of capacity. Varying the build rates according to the physical constraints and taking into consideration government plans for deployment will enable a range of pathways to be explored and subsequently determine how CCS build rates may influence the diversity of the UK electricity system.

It is of course also possible to generate a set of scenarios with lower build rates than those set out in this thesis, however, this would not allow the ambitions for CCS technologies set out above to be met and in light of the fact that the IEA (2009) suggests that CCS is essential in achieving emission reductions at up to 70% of the cost without; this has not been pursued in this thesis.

The build rate constraints used in this thesis are set out in Table 8 and the build rates for other large generation technologies provided in Table 9 for reference.

Table 8 – Summary of CCS build rate scenarios

	2000	2005	2010	2015	2020	2025	2030-2050
Reference	2.5	2.5	2.5	2.5	2.5	2.5	5.0
Central	5.0	5.0	5.0	5.0	5.0	5.0	10
High	7.5	7.5	7.5	7.5	7.5	7.5	15
High-High	10	10	10	10	10	10	20

Note - figures are given in GW and represent the total maximum installed capacity of CCS technologies over the given five year period.

Table 9 – Build rate constraints for large generation technologies

MARKAL Technology	Reference Scenario Constraint
Large Coal Plant	0.5GW per annum 2000-2025, 1GW per annum 2025-2030, 2GW per annum 2030+
Large Natural Gas Power Stations	0.5GW per annum 2000-2025, 1GW per annum 2025-2030, 2GW per annum 2030+
Carbon, Capture and Storage (Coal and Gas)	0.5GW per annum 2000-2025, 1GW per annum 2025-2030, 2GW per annum 2030+
Marine Renewables (tidal and wave)	0.5GW per annum 2000-2025, 1GW per annum 2025-2030, 2GW per annum 2030+
Wind (on and offshore)	0.5GW per annum 2000-2025, 1GW per annum 2025-2030, 2GW per annum 2030+
Nuclear	0.5GW per annum 2000-2025, 1GW per annum 2025-2030, 2GW per annum 2030+
Distributed Generation (gas, H ₂ , micro-wind)	0.5GW per annum 2000-2025, 1GW per annum 2025-2030, 2GW per annum 2030+

Note - for large generation technologies in MARKAL the reference scenario constraints are applied to all other scenarios generated.

5.3.1.3.2 Fossil Fuel Assumptions

The DECC fossil fuel assumptions are used to generate scenarios for this thesis as discussed. The numerical projections for each scenario can be found in Table 10. This set of assumptions and used in this thesis because they are UK specific and cover a range of price scenarios from very low fossil fuel prices to very high fossil fuel prices. It is important to acknowledge that there may be further price extremes with fossil fuel prices may rising above those in the high-high scenario shown, however, these assumptions provide a good basis for exploring a number of different pathways and to explore the influence that fossil fuel prices may have on the diversity on the scenarios generated. Extending them further falls outside the scope of this thesis.

Table 10 – DECC Fossil Fuel Price Assumptions

Scenario	Fuel	2000	2005	2010	2015	2020	2025	2030	2050
Low	Oil	4.12	9.35	4.58	5.31	5.50	5.50	5.50	5.50
	Gas	1.93	4.47	2.62	2.70	2.70	2.77	2.77	2.77
	Coal	0.91	2.97	1.62	1.01	1.01	1.01	1.01	1.01
Central	Oil	4.12	9.35	6.41	6.87	7.33	7.79	8.25	8.25
	Gas	1.93	4.47	4.47	4.85	5.16	5.47	5.70	5.70
	Coal	0.91	2.97	2.23	1.62	1.62	1.62	1.62	1.62
High	Oil	4.12	9.35	7.70	11.00	11.00	11.00	11.00	11.00
	Gas	1.93	4.47	5.39	6.40	7.47	7.47	7.47	7.47
	Coal	0.91	2.97	2.43	2.02	2.02	2.02	2.02	2.02
High High	Oil	4.12	9.35	9.44	13.01	13.74	13.74	13.74	13.74
	Gas	1.93	4.47	6.47	8.71	9.17	9.17	9.17	9.17
	Coal	0.91	2.97	2.63	2.63	2.63	2.63	2.63	2.63

The low scenario reflects an overall low global energy demand with a deep global recession extending to 2011 followed by a period of slow growth in global GDP. Global energy demand decreases initially and subsequently grows at a slower rate than previous trends and energy supplies increase as result of successful investment. An increase in competitive pressure in liberalised markets leading to prices reflecting the long term marginal supply costs. In addition strong competition arises from technological advancement and investment in low carbon technologies. The central scenario reflects an overall timely investment in low carbon technologies with moderate energy demands. The global recession extends to 2010 and in the short term low energy demands keeps prices low. In the medium term global economic growth improves and pushes up energy demand and timely investment ensures that supply is sufficient to meet the growing demand. The high scenario reflects high energy demand and producers market power. The global recession affects energy demand in 2009 this starts to pick up strongly in 2010. The emerging markets grow strongly placing pressure on energy markets and subsequent supply shortages increase the market power of the dominant players. Substitution of fossil fuels to non-fossil fuel power sources is limited and expensive with delays in investment and slow

technical advancement. In the high-high scenario energy demand is high and there are significant supply constraints. The global economy recovers quickly from the global recession from 2009 onward and rapid energy demand growth coincides with slow investment in energy supply, leading to price increases. Delays in investment of alternative technologies and fuels are relatively expensive and substitution of technologies becomes limited as they are not economically viable (Usher and Strachan, 2010, Greenacre, 2012).

Please refer to sections 4.3.7.2 and 5.3.1.1.4 for more details.

Each scenario is referred to as following, FFP-L (low fossil fuel price scenario), FFP-C (central fossil fuel price scenario), FFP-H (high fossil fuel price scenario), FFP-HH (high-high fossil fuel price scenario).

5.3.1.3.3 CCS Capital Cost Constraints

Some low carbon technologies such as wind and nuclear have already been proven and installed at a significant commercial scale across the world. However, CCS technologies, as we have already seen, have not yet been proven at the commercial level with limited demonstration facilities currently in place. Therefore, the relative cost figures for CCS technologies, as well as other unproven technologies such as wave power, depend on comparisons between the actual costs of one technology and the estimated future costs of another.

The capital costs for CCS (including capital, fixed and variable costs) are taken from reports by Mott MacDonald (2010) and Parsons Brinckerhoff (2011). Both of these reports were commissioned by DECC (and contain the most recently published technical data for CCS technologies containing all data parameters required for MARKAL) to make an assessment of current and forward power generation costs for the main large-scale technologies applicable to the UK. It is important to note, that in generating these reports, many factors are taken into consideration, including the exact technology details, the scale for deployment and the numbers of plant orders, suppliers selected, ruling market conditions and the ability of the developer to manage costs. This is particularly poignant for unproven technologies such as CCS and one of the first challenges for considering technologies like this to understand the extent of

the first of a kind premium, which in part, depends on the responsiveness of the supply chains.

In determining the capital costs for CCS technologies, these two reports have made several assumptions, firstly, that all CCS technologies will compress CO₂ into a pipeline network for transport to underground sequestration sites; the costs of transport and storage are factored in based on a user charge per tonne of CO₂ captured (future carbon costs extrapolated) and finally, that all new plant orders from 2010 will be required to be designed to be capture-ready in accordance with an EU directive implemented in April 2009. Thus, with no existing, utility scale carbon capture installation on working power plants, all estimates have to be made from scaling up prototypes and detailed bottom-up engineering estimates or vendors preliminary estimates. With this in mind it is clear that estimating the cost of CCS technologies is surrounded by significant uncertainty and that this must be taken into consideration when using such estimates.

Uncertainty does not just apply to CCS technologies. Other technologies such as nuclear power that are already proven at the commercial level still have a large degree of uncertainty regarding their cost. More specifically, looking back very briefly at the history of nuclear power, cost projections and actual costs were very different and some of the first reactors which began construction in the late 1960s cost twice as much as originally estimated and that reactors which began construction following those just mentioned actually cost more than three times the projected costs of the first set of reactors (Greenacre, 2012). There are of course, many factors surrounding this difference including various methodological, strategic, technical and / or practical issues, however, it is a good illustration of the variation between cost estimates and actual costs. This provides a substantial rationale for exploring the effects of varying capital costs of CCS technologies using MARKAL.

Prior to running the scenarios for this thesis, there were no published MARKAL (MED version) scenarios that had varied capital costs to explore the effect that this would have on the deployment of CCS technologies. This is an important aspect to explore further in relation to the various targets set for CCS deployment as discussed earlier in

this thesis and how increasing or indeed decreasing capital costs may affect this outcome. Thus, this thesis takes the most up to date costs assumptions discussed above, to generate a set of scenarios to explore this in more detail. These 'baseline' costs will be multiplied by a factor of 0.5 (to halve CCS capital costs), 1.0 (reference), 1.5 (to increase CCS capital costs by half) and 2.0 (to double CCS capital costs) respectively. The justification for this range of scenarios takes into consideration two points:

Firstly, for the scenarios where capital costs are increased the various estimates that have been made previously for both nuclear power cost escalations and coal power escalations have been taken into consideration. In relation to coal cost escalations, Joskow and Rose (1985) highlight that the real costs of coal between the 1960's and 1980's increased by 80%. In relation to nuclear cost escalations the following studies are highlighted by Greenacre (2012):

- a. Tolley and Jones (2004) – estimate that by the time a new plant comes online, total capital costs can be 25-80% greater than the overnight costs, depending, of course on interest rates and the length of construction.
- b. Harris (2012) – analysis suggests that overnight construction cost estimates made between 2005 and 2011 have increased on average by 17.5% per annum above the rate of inflation.
- c. Parsons Brinckerhoff (2010) reports suggest that estimates of nuclear generation costs rose by 40% between 2008 and 2010, with levelised costs approximately doubling between 2006 and 2011.

Thus, with coal and nuclear cost escalation ranging from a 25% increase to a 100% increase, this is the justification for the high and the high-high scenario to increase capital costs by 50% and by 100%.

For the scenario where capital costs are halved, the report by the CCS Reduction Task Force (2013) was taken into consideration and its key conclusion that UK gas and coal power stations equipped with CCS have the clear potential to deliver electricity at a levelised cost approaching £100/MWh by the early 2020's, and at a significantly lower costs soon thereafter. This report suggests that first set of CCS projects will have

levelised costs in the range of £150-200/MWh and highlights that a major factor in reducing these costs to meet its ambition would be the significant reduction of capital costs (alongside reductions in storage and transport). The assumptions applied in achieving these reductions are based on technologies that are already widely used at large scale i.e. coal power, that can be invested in with confidence and manageable risk. With this estimated reduction in costs by about half, it would be interesting to look at a scenario where we seek to achieve this ambition and look at the subsequent effect it would have on the diversity of the UK electricity system.

It is important to note that capital costs could be increased beyond the levels set out in these scenarios; however, the scenarios selected here provide a good basis for exploring the effect of capital costs on the deployment of CCS technologies and subsequently its effect of the diversity of the UK electricity system.

5.3.2 Generating Diversity Profiles for Scenarios

The next part of this chapter is dedicated to the generation of diversity profiles for each of the scenarios generated. Profile generation was carried out in two stages. Firstly, in the absence of interview data a 'standard' disparity matrix was generated to enable the calculation of diversity and create the profile and secondly with interview data, to generate 'individualised' disparity matrices used to calculate diversity and diversity profile. This subsequently enabled us to see how the overall diversity profile according to how differently an interviewee perceives technologies to be from one another.

5.3.2.1 Stage 1 – without interview data

Step 1 - Calculation of variety and balance

Calculation of $p_i p_j$ (the proportional representations of option i and option j in the energy system).

Scenario generation creates a number of different output parameters. The most suitable output parameters to use for exploring changes to the electricity system are installed capacity and electricity generation (see Chapter 6 for more detail) and are used to create separate profiles. Each of these output parameters is generated by the

model for each technology at each 5-year time point between 2000 and 2050. This data is used to calculate the proportional contribution that each technology makes to electricity generation. This is calculated by dividing the value of the electricity generated for each technology option by the total electricity generated for all technologies in that year. This data is then taken to create a matrix of p_{ij} in which all the proportional contributions for each of the different energy options are multiplied by one another for each 5-year increment. This matrix then goes onto to be multiplied by the matrix for d_{ij} , described in the proceeding text.

Step 2 – Calculation of disparity

Calculation of d_{ij} (the distance separating options i and option j in disparity space)

In order to calculate the distance in disparity space between each energy option the different attributes upon which this is based must first be determined. The technology 'performance data' from MARKAL for each of the technologies was used. This 'performance data' is a set of variables, which describes the different technical and cost parameters for each technology including: electrical efficiency; contribution of the technology to peak load; availability factor, plant lifetime, capital costs, fixed operation and maintenance costs, and the variable operation and maintenance costs (see Table 11 for definitions).

Table 11 - Summary of technology performance data criteria

Criteria	Definition of Criteria
Availability Factor	The amount of time that a power plant is able to generate electricity over a given time frame
Electrical Efficiency	The ratio between useful electricity output from the generating plant and the total power consumed in the generation of this electricity
Capital Costs	Final cost of investing in a new power plant in the UK is represented by this figure, however, individual site of company specific details are not considered
Fixed Operation and Maintenance Costs	Costs incurred regardless of whether the plant is operating or not
Variable Operation and Maintenance Costs	Costs incurred when the plant is in operation which vary according to output
Plant Lifetime	The number of years a plant is operational, planning and construction of the plant are not included in this figure
Contribution to Peak Load	The maximum % percentage contribution that a plant is able to make to the peak load

These input parameters were selected and used as ‘attributes’ for this exercise for several reasons. The main reason is that this data characterises the different technologies and to a significant extent, it ‘captures’ the physical and other differences between technologies such as how capital intensive they are, what they costs to run, how efficient they are etc. Hence, the data shows overall how different technologies are from each other according to these attributes. Secondly, these attributes drive technology selection in each of the scenarios and finally, the relative ease of availability of this data. There are indeed numerous attributes that could be selected in addition to the input parameters used in this instance (i.e. such as various environmental, security or public acceptability measures), however, defining these for over each of the technologies in MARKAL (more than 100) is an enormous task and beyond the scope of this thesis. Thus, in the later analysis and subsequent discussion of diversity in this thesis, this must be taken into consideration.

The data for each technology is entered into an Excel spreadsheet; the user interface for a multi-criteria diversity analysis³⁵ programme written in Matlab and is used to generate disparity matrices in this thesis. This tool uses the Ward Method of Cluster Analysis (cluster analysis is a multivariate method which classifies samples based on a set of measured variables into a number of different groups such that similar subjects are placed in the same group) an agglomerative hierarchical clustering method to create a matrix describing the distance separating each of the energy options in ‘disparity space’.

Specifically, the Ward Method allows energy options (subjects) to be partitioned into clusters in a series of steps of successive clustering of the individual energy options into groups. During this process every possible pair of clusters is considered and the fusion of energy options to form a cluster arises results from a minimum increase in ‘information loss’ when combined (Everitt, 1993). Therefore in the case of this thesis, energy options are clustered according to how closely associated their technology performance data is related. This begins with each energy option initially considered a single cluster to the final stage where technologies form a series of clusters according to how closely associated they are based on their performance data (Everitt and Dunn,

³⁵ MDA tool developed in house at SPRU by Andrew Stirling, Go Yoshizawa and Toby Champion

1991). This accurately reflects the distinguishing features of the electricity generating energy options (Kruskal, 1964, Stirling, 2010), taking into account the constraints of data availability. This is represented in 'disparity space' by taking the distance between two options for each individual attribute and then combines them in n-dimensional Euclidean space using a sum of squares approach. Thus $d_{ij} = \sqrt{(\alpha_1^i - \alpha_1^j)^2 \cdots (\alpha_N^i - \alpha_N^j)^2}$ where α_x^i is the value of attribute x for option i (Skea, 2010) and can numerically be represented in the form of a matrix.

For the reference scenarios, in the absence of interview data, a 'standard' disparity matrix is generated and no weightings are placed on any of the attributes. Weightings are used in Stage 2 to allow interviewees to describe the relative importance they place on each of the attributes in determining how different technologies are from one another.

The disparity matrix can be visualised using a dendrogram (see Figure 18), also referred to as a tree diagram which shows using a series of vertical lines to show the relationships between different clusters. A dendrogram should be read from left to right and each of the lines represent clusters which are joined together and the position on the line of the scale represents the distances at which clusters are joined. The further the distance between clusters the more distinct clusters are from one another and the more different technologies are from one another.

There are several different clustering methods that could be used to represent the multidimensional distribution of disparities in the dendrogram; however, this could be considered the most appropriate. However, it is important to note that the representation of disparity in this way has not yet been perfected and that there may be losses of information when compared to the original multi-dimensional distribution itself. It is important to remember that the dendrogram simply provides a convenient visual guide to the underlying structure of the data and that this simple graphical representation helps the reflexive understanding of the structure of option disparities that is implicit to the data (Yoshizawa, 2009). With this in mind it is important to note that dendrograms should not be interpreted too literally or indeed measured with a ruler to find out how disparate the technologies are from one another.

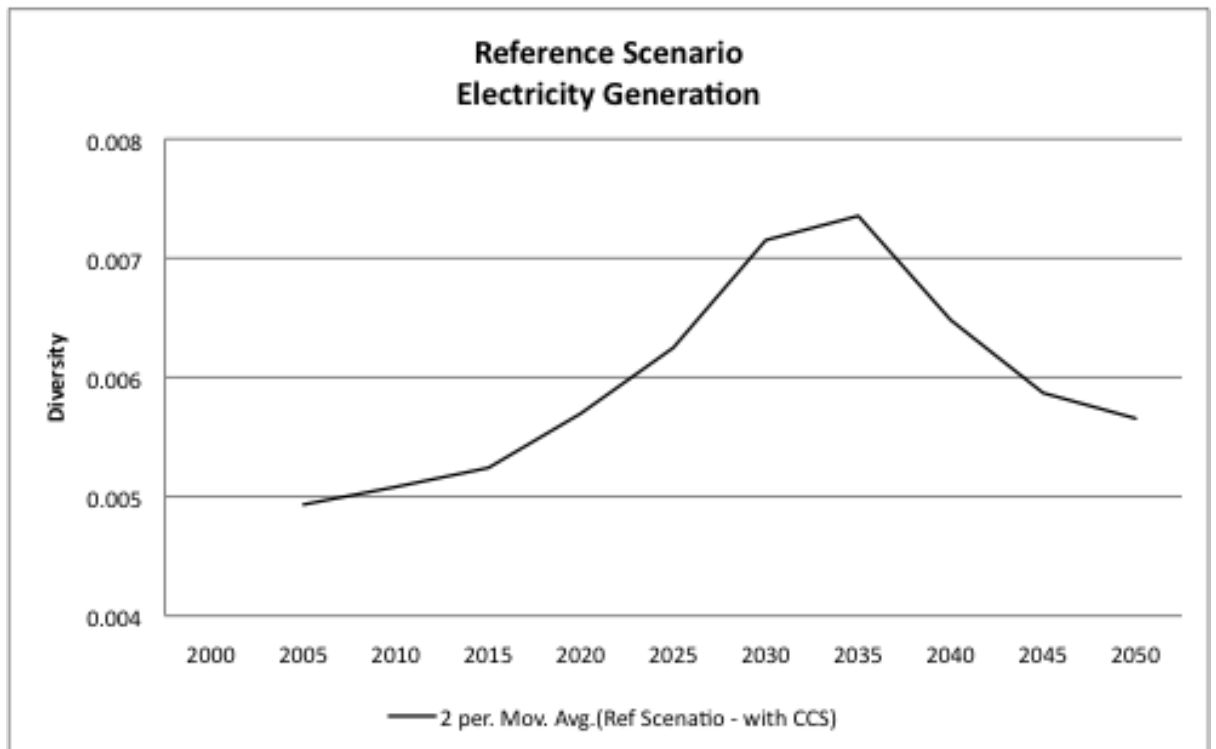
Step 3 – Calculation of diversity

The final step in the calculation of diversity requires the summation across the half matrix of $((N^2-N)/2)$ non-identical pair options $(i \neq j)$ of $(d_{ij})(p_i p_j)$.

$$D = \sum_{ij(i \neq j)} d_{ij} \cdot p_i \cdot p_j$$

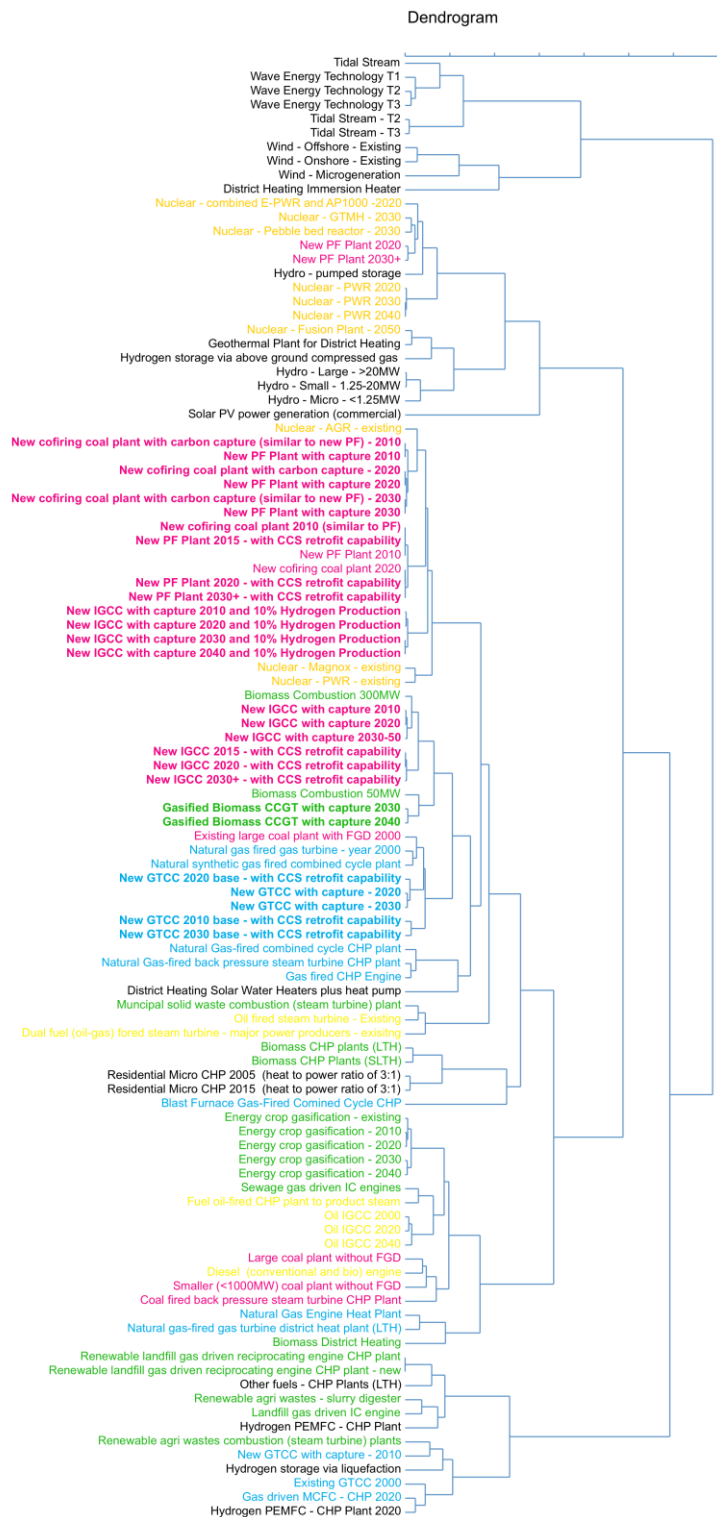
This final step generates a value for diversity for each 5-year time point between 2000 and 2050. This can be visualised by plotting the data on a line graph, referred to for the rest of this thesis as a ‘diversity profile’ and the change in diversity seen over time (see Figure 17). The diversity profiles were plotted using a moving average. This is a technique frequently used for isolating the trend from time-series data by smoothing out short term fluctuations in the data which is achieved by averaging successive observations (Barrow, 2013). A two-period moving average is applied to this data, which means that the data for two successive points is averaged resulting in the diversity profiles, starting from 2005, not 2000, the base year.

Broadly, the diversity profile in Figure 17 shows that the diversity of electricity generation rises to a peak in 2035, before falling to approximately half of the overall increase in diversity seen. It is important to point out at this point, that the absolute values for diversity on the vertical axis are very low i.e. between ~ 0.005 and 0.008 in this scenario. Increasing the value of either the variety or balance of technologies will increase the value of diversity of the scenario. However, due to the large number of technologies in the model which are arranged in ‘disparity space’ according to the similarity of their different attributes, the resulting distance between technologies in ‘disparity space’ is relatively low resulting in low absolute values for diversity for the scenarios. Moreover, this also suggests that the technologies are rated quite similarly by quite different ‘attributes’ or ‘dimensions’.

Figure 17 – Example Diversity Profile

Each modelling scenario generated was used to generate a diversity profile, first using the disparity matrix in Stage 1 and later using 'individualised disparity matrices' from interviewees as described in the next section. This enabled a comparison of diversity profiles across all of the scenarios in order to address research question 2 (see section 5.2).

Figure 18 - Example Dendrogram illustrating the output of technology performance appraisal



Note – Red – Coal technologies, Blue – Gas technologies, Green – Biomass technologies, Orange – Nuclear technologies, Black – Renewable technologies, Yellow – Oil technologies, CCS technologies in bold.

5.3.2.2 Dendrogram Interpretation

It is important to remember that dendrograms show the structure of underlying option disparities implicit from the attributes from MARKAL derived using the Ward Method of Cluster Analysis. The lines on the dendrograms indicate the hierarchical clustering of technologies and are referred to as branches. The arrangement of the branches tells us how similar or different the various technology options are from one another and are found at the terminal end of the branches. Each fusion of two clusters is represented on the graph by the splitting of a horizontal line into two horizontal lines. The horizontal position of the split shown by the short vertical bar gives the distance (dissimilarity) between the two clusters.

Looking at the dendrogram more generally it is clear to see from the colour coding of different technology groups, that technologies within these groups, tend to, as a rule of thumb be clustered fairly closely together, suggesting the underlying disparity structure of these technologies is closely related. Note - *the dendrogram discussed here is the reference scenario (using the 'standard' disparity matrix) dendrogram and a more detailed description and analysis of this dendrogram, including a discussion of the clustering of CCS technologies will be made in Chapter 7 (Empirical Analysis II)),*

Using the top ten technologies on the dendrogram as an illustration, there are three distinct clusters:

- **Cluster 1** – wave energy technology T2 and T3 are the most similar technologies; wave energy technology T1 and tidal stream are outlier technologies to this cluster and are fused at greater distances.
- **Cluster 2** – tidal stream 2 and tidal stream 3, there are no outlier technologies in this cluster.
- **Cluster 3** – Wind offshore and wind onshore (existing) are fused with two outlier technologies; wind micro generation and district heating immersion water.

Using the data from each of the attributes for the technologies in the three clusters (see Table 12), we can begin to understand the relationship between these technologies.

In cluster 1, Wave Energy T1 and T2 and T3 have 6 identical attributes, the non-identical attribute is capital costs which differ by approximately 20% between Wave Energy T2 and T3 and T1 varies by a further 17%. This greater variation of Wave Energy T3 results in it not being immediately clustered with Wave Energy T2 and T3 but positioned as an outlier to this cluster. The other outlier in this cluster, the greater outlier of the two is Tidal Stream, which has

In cluster two, Tidal Stream 2 and 3 have 6 identical attributes with the non-identical attribute being capital cost; however the difference in cost between the two technologies is just 11%. Tidal Stream 1 varies in cost from Tidal Stream by 80% and this is why it appears in cluster 1 and not cluster 2, despite its other attributes being identical to Tidal Stream 2 and 3 technologies. Thus despite their similarities in 6 attributes, the effect of the dissimilarity in capital cost is enough to separate the technologies into different clusters. There is however a branch from cluster 2 across to the outliers in cluster 1 highlighting a degree of similarity so Tidal Stream is not completely removed from Tidal Stream 2 and 3.

In cluster 3, wind offshore and wind onshore (existing) technologies form a cluster, they have 4 identical attributes, with variation in the availability factor of the two technologies, the capital costs and the fixed O&M costs. The most similar outlier technology to this cluster is wind micro generation; wind micro generation is more closely associated with onshore wind according to its position from the cluster. District Heating Immersion Water is the greatest outlier from this cluster and with availability factor and capital costs varying significantly from the various wind technologies but similarities in electrical efficiency, contribution to peak load and variable O&M costs. There is a branch from this cluster connecting it to the other two clusters, indicating degrees of similarity between the technologies and illustrating that although technologies appear in different clusters, they are not completely dissimilar from one another.

Table 12 – Technology Performance Data for technologies 1-10 featured within the first three clusters in Figure 18

Technology	Availability Factor	Electrical Efficiency	Capital Cost	Fixed O&M Cost	Variable O&M Cost	Plant Lifetime	Contribution to Peak Load
Wave Energy T1	20	45	4113	488	0	30	18
Wave Energy T2	20	45	5077	488	0	30	18
Wave Energy T3	20	45	6101	488	0	30	18
Tidal Stream	51	100	1948	376	0.3	30	33
Tidal Stream T2	51	100	8898	376	0.3	30	33
Tidal Stream T3	51	100	9854	376	0.3	30	33
Wind Offshore (existing)	35	100	1315	45	0	25	43
Wind Onshore (existing)	26.4	100	675	27	0	25	43
Wind Microgeneration	20	100	1350	27	0	25	0
District Heating Immersion Water	100	100	7.9	0.2	0	15	0

5.3.2.3 Stage 2 – with interviewee data

This second stage of this methodology repeats this process for each scenario but this time involves weighting the different technology attributes to reflect an individual's perspective on how different technologies are from one another. Weighting the attribute required asking interviewees to provide a numerical value between 0 and 100 for each attribute according to their relative importance in determining how different technologies are from one another. These scores are then normalised and it is the relative importance of these performance differences that are being compared and weighted.

An 'individualised' disparity matrix for each stakeholder can then be produced in the same way as in Stage 1, however, with the weightings provided by the interviewee applied.

This protocol varies from the original suggested by Stirling and Yoshizawa (2009) in which both the energy options and attributes are selected by the interview participants at the beginning of the process. Obtaining data for all attributes defined by an interviewee for the 104 generation technologies contained with MARKAL is beyond the scope of this thesis due to time constraints, thus the technology performance data contained with MARKAL was used instead as discussed previously. However, the interviewee *is* provided with the opportunity to appraise the actual performance data, identify any areas that they did not agree with and amend as

appropriate as well as identifying any further attributes to be added at the end of the process.

The additional attributes provided by interviewees are any that they deemed relevant to the question '*how different are technologies from one another*' and where possible indicate the data relevant to these criteria for each technology quantitatively, in the same way as the MARKAL data. However, these additional attributes were approached using a simple yes/no system (quantitatively inputted into the model using the values 0 and 1 respectively). This was because obtaining the specific data for each of these additional attributes was beyond the scope of this thesis; due to the time it would take to collect such data and the limited availability of such data for all of the technologies specified in MARKAL. A simple example of an additional attribute may be '*is this a fossil fuel technology?*' Additional attributes were then subject to scoring in the same way as the original criteria were.

Each scenario was analysed for a second time using the same protocol in Stage 1 but this time disparity matrices generated from the stakeholder interviews were added. This process allows the impact of different stakeholder perspectives on the disparity of technologies to address research question 3 (see section 5.2). Additional attributes added by participants were analysed in 2 cases and are discussed separately later in this thesis (see section 7.3).

5.3.2.4 Identifying interview participants

Interview participants were identified from organizations involved in the CCS debate in the UK and enlisted accordingly. CCS experts as opposed to more general energy industry experts were selected because of their specialist knowledge on both the cost and technical aspects of CCS technologies (data key in determining disparity matrices for this thesis). The organizations approached included private industry with an interest in CCS, green think tanks, non-governmental organizations and academics involved in CCS research both policy and technically-based, non-technical trade associations and public sector organizations. The list of participants can be seen in Table 13.

Table 13 – List of interview participants and their institutional affiliations

Interview ID	Institutional Affiliation
SPA1	CCS Programme Manager, Energy Technologies Institute (ETI)
SPA2	Senior CCS Advisor, UK Environment Agency
SPA3	Chief Executive, Carbon Capture and Storage Association (CCSA)
SPA4	CCS Specialist, Scottish and Southern Electric (SSE)
SPA5	Senior Modelling Academic, UCL Energy Institute
SPA6	Senior Engineering Academic, Imperial College
SPA7	Technical Head, EON
SPA8	Senior Policy Advisor, Green Alliance
SPA9	Head of Climate Change and Energy, Greenpeace
SPA10	Senior Energy Analyst, IEA Clean Coal Centre
SPA11	Senior Policy Academic, UK Energy Research Centre (UKERC)
SPA12	Senior Policy Academic, SPRU, University of Sussex
SPA13	Senior Policy and Planning Officer, Royal Society for the Protection of Birds (RSPB)

5.4 Chapter Summary

This chapter has set out the research questions and gaps in the literature that this thesis seeks to address. In doing so it has also set out the different methodologies selected to do this and provided a detailed explanation of these methodologies as well as providing reasoning for the selection of each of the methodologies.

In Chapter 6 a descriptive analysis of the MARKAL scenarios will be presented in Part A. In Part B, the diversity analysis for each scenario will be presented in the form of diversity profiles. These will be presented in the first instance using value for disparity derived from the technology sub-module of MARKAL with the same or equal weighting placed on any of the criteria. These scenarios will then be presented with the results of stakeholder participation (providing alternate values for disparity), which are used to generate ‘individualised’ diversity profiles for each scenario for comparison.

CHAPTER 6. Empirical Analysis I

6.1 Chapter Introduction

This chapter provides an analysis of the scenarios generated for this thesis. In doing so, it discusses how varying selected input assumptions affects model projections of installed generating capacity and electricity generation in the UK. It then goes on to investigate the corresponding impacts on the diversity of the UK generating system.

In the next empirical chapter a series of stakeholder interviews are analysed in the context of disparity. Each individual's perspectives on the partitioning of energy options derived from the technologies incorporated into MARKAL are considered for each scenario in turn and compared.

6.2 MARKAL Scenario Run Results

In total two reference scenarios (one run with and one run without CCS) and 9 further scenarios were run; summarised in Table 15. As discussed in more detail in Chapter 5, these scenarios have been run to explore the effects of varying CCS build rate assumptions, CCS capital cost assumptions and fossil fuel price assumptions in order to explore how varying these assumptions may affect the deployment of CCS and the subsequent impacts this may have on the diversity of the system. For each of these scenarios a number of key assumptions are kept constant and these are summarised in Table 14 and Table 16 for reference.

Table 14 - Summary of key assumptions and constraints for the reference scenarios.

Parameter	Assumptions
Emission Constraint	80% reduction in carbon emissions by 2050 based on 1990 levels according to UK climate targets.
Hurdle Rate Constraint	10% for power generation technologies
Policy Constraints	Renewables Obligation included, DECC Carbon Floor Price included, feed in tariffs for solar PV, micro-CHP, micro-hydro and wind, DECC Carbon Targets to 2020 to be met
Fuel Price Constraints	DECC Central Fuel Price Assumptions
Energy Demand Constraints	BERR Energy Demand Model assumptions
Build Rate Constraints	Max. 0.5GW per annum from 2000-2029, Max. 1GW per annum from 2030-2050

Table 15 – Summary of MARKAL Scenario Runs

Scenario	Summary of Input Assumptions
REFERENCE SCENARIO (with CCS) Referred to as scenario A	CCS technologies available to the model
REFERENCE SCENARIO (without CCS) Referred to as scenario B	CCS technologies <u>unavailable</u> to the model
BUILD-L (low build rate assumptions) <i>CCS build rate constraints ONLY changed</i>	Max. 0.5GW per annum from 2000-2029 Max. 1GW per annum from 2030-2050
BUILD-H (high build rate assumptions) <i>CCS build rate constraints ONLY changed</i>	Max. 1.5GW per annum from 2000-2029 Max. 3GW per annum from 2030-2050
BUILD-HH (high-high build rate assumptions) <i>CCS build rate constraints ONLY changed</i>	Max. 2GW per annum from 2000-2029 Max. 4GW per annum from 2030-2050
CCS-L (low capital cost assumptions)	Baseline costs of CCS only multiplied by 0.5
CCS-H (high capital cost assumptions)	Baseline costs of CCS only multiplied by 1.5
CCS-HH (high-high capital cost assumptions)	Baseline costs of CCS only multiplied by 2.0
FFP-L (low fossil fuel price assumptions)	DECC Fossil Fuel Assumptions – Low Scenario
FFP-H (high fossil fuel price assumptions)	DECC Fossil Fuel Assumptions – High Scenario
FFP-HH (high-high fossil fuel price assumptions)	DECC Fossil Fuel Assumptions – High-High Scenario

Table 16 – Summary of key assumptions and constraints for build rate, capital costs, fossil fuel price and hurdle rate scenarios

Parameter	Key Assumptions
Emission Constraint	80% reduction in carbon emissions by 2050 based on 1990 levels according to UK climate targets.
Hurdle Rate Constraint	10% for power generation technologies (<i>except in the hurdle rate scenarios where this is varied</i>).
Policy Constraints	Renewables Obligation included, Carbon Floor Price included, feed in tariff's for solar PV, micro-CHP, micro-hydro and wind, DECC Carbon Targets to 2020 to be met
Fuel Price Constraints	DECC Central Fuel Price Assumptions (<i>except in the fossil fuel price scenarios where this is varied</i>).
Energy Demand Constraints	BERR Energy Demand Model assumptions
Build Rate Constraints	Max. 0.5GW per annum from 2000-2029, Max. 1GW per annum from 2030-2050

6.2.1 Reference scenario results

Two reference scenarios were run, one *with* the option for the model to deploy CCS technologies (referred to from here as **Scenario A**) and one *without* the option for the model to deploy CCS technologies (referred to from here as **Scenario B**).

6.2.1.1 Scenario A

The scenario results that are used to explore portfolio diversity in this thesis are electricity generation and installed capacity. These two parameters have been selected because alone, neither of them provides a complete picture of the electricity generating portfolio. Electricity generation, for example, does not adequately reflect

technologies that have been installed but are little used for reasons such as load factor constraints which can lead to higher generation costs. Load factor refers to the actual output of the plant divided by the maximum technically possible load (also referred to as the peak load) over a given time period, calculated as a percentage. High load factors indicate that power output from a plant is relatively constant resulting in the generation of cheaper electricity. If a plant has a lower load factor, it produces less electricity resulting in higher system costs for the production of each kWh of electricity. In the instance of the CCS plants, both coal and gas plants have relatively high load factors, however, the lower annual fixed costs of gas results in the model favouring the generation of electricity from gas rather than coal because it seeks to optimise cost. A comparison of these figures for coal and gas CCS plants in the model is presented in Table 17.

Table 17 – Selection of coal and gas CCS technologies from the MARKAL model and their respective load factors, capital costs and fixed costs.

Technology	Load Factor (%)	Capital Costs (£/kW)	Fixed Costs (£/kW/year)
New GTCC with capture - 2010	89.5	1092.0	25.0
New GTCC with capture - 2020	89.5	802.8	30.2
New GTCC with capture - 2030	89.5	768.4	30.2
New PF Plant with capture 2010	89.0	1917.9	62.8
New PF Plant with capture 2020	89.0	1750.1	62.8
New PF Plant with capture 2030	89.0	1615.9	62.8
New IGCC with capture 2010	88.0	1910.0	56.4
New IGCC with capture 2020	88.0	1795.4	56.4
New IGCC with capture 2030-50	88.0	1633.0	56.4

**GTCC – gas, PF and IGCC - coal*

The first of these results to be discussed is installed capacity; this enables us to look at the composition of the energy system before looking at the mix of electricity from these options in each scenario.

Scenario A (Figure 19) shows unabated coal and gas dominate the mix from 2000 to 2015 which is also reflected in the data for electricity generation. Nuclear technologies also make a significant contribution with a maximum capacity in 2000 of ~12GW. The decline in capacity for these technologies can be attributed to fleet retirement. These

fleets are replaced by other low carbon and renewable technologies as the scenario progresses and various emission constraints must be met and policy assumptions are applied.

From 2015, in terms of renewable technologies, there is growth in on and offshore wind reaching a peak capacity of 10-11GW in 2030. However from 2030, the capacity of offshore wind starts to decline to less than 1GW by 2050. This is due to the relatively short lifetime of offshore wind technologies in the model of 25 years. The technology is then not replaced by the model but instead the deployment of other technologies such as tidal and wave increases, reaching a capacity of ~15.5GW by 2050. Hydro technologies also make a significant and consistent contribution to capacity of ~4GW from 2020-2050 and biomass technologies also feature strongly, contributing up to 7-8GW of capacity from 2025. With regards to low carbon technologies, the capacity of CCS technologies increases as the capacity of unabated coal and gas drops off with the peak capacity of CCS technologies reaches ~15GW from 2030 onwards (this is about half of the capacity of unabated gas or coal at their peak). Nuclear technologies as identified, also contribute significantly towards capacity at the beginning of the scenario falling to ~7.5GW in 2015 but heavy investment in nuclear technologies results in the technology reaching a peak capacity of ~20GW by 2050.

Figure 19 – Scenario A results

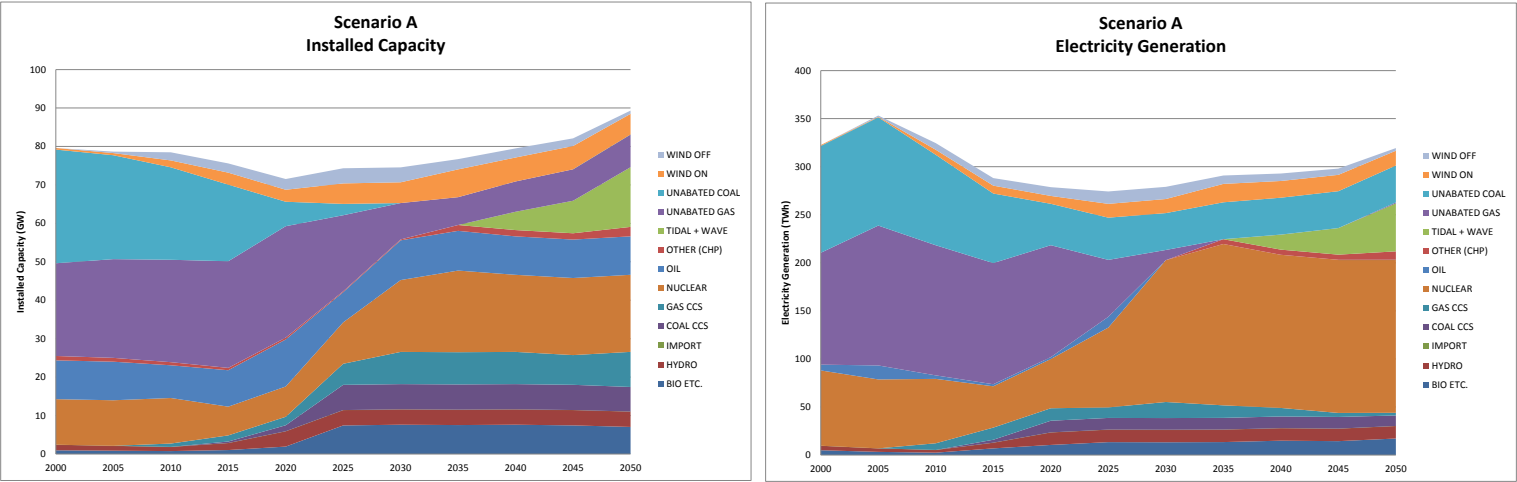
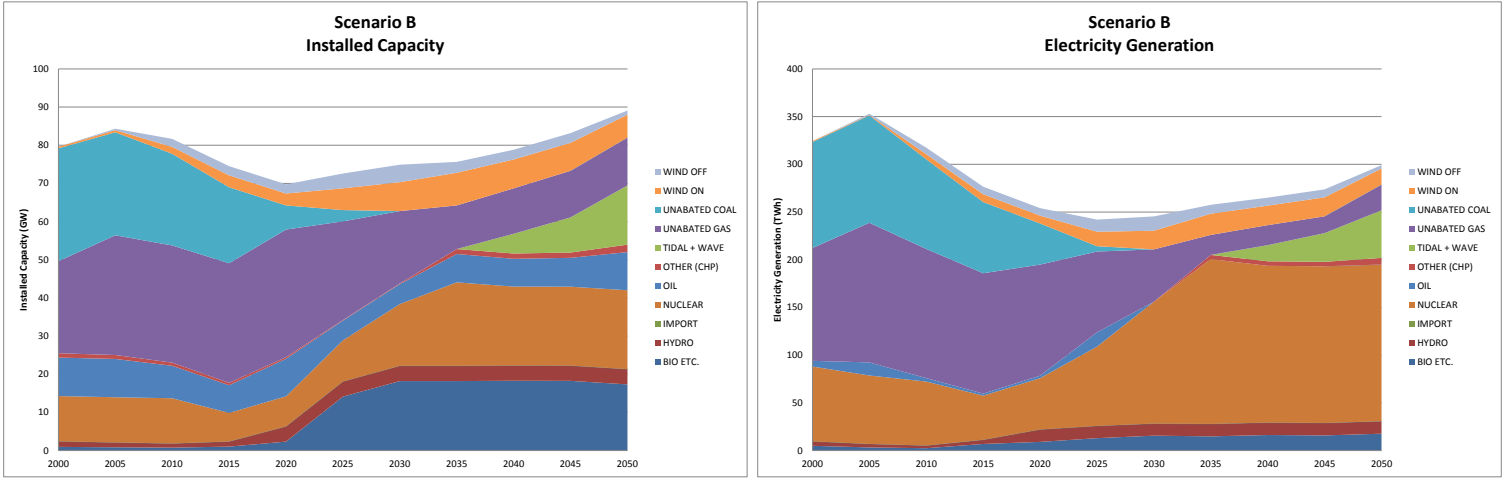


Figure 20 – Scenario B results



6.2.1.2 Scenario B

The results for Scenario B show a different story to Scenario A in the absence of CCS which is why they are discussed separately. The diversity profiles of the both of the reference scenarios are discussed together following this section.

The results for the installed capacities of Scenario B show that (see Figure 20) unabated coal and gas dominate the mix from 2000 to 2015 (also reflected in the data for electricity generation). These technologies then decline. Unabated coal falls to ~3GW by 2025 and by 2030 no longer features in the electricity mix for the UK. Unabated gas also declines but not to the same extent as coal and falls to its lowest capacity in 2040 of ~12GW. The decline in capacity for these technologies can be attributed to fleet retirement. These fleets are replaced by other low carbon and renewable technologies as the scenario progresses and various emission constraints must be met and policy assumptions are applied.

Nuclear technologies also make a significant contribution; in 2000 capacity is ~12GW. This declines to ~7.5GW in 2015, attributable to existing fleet retirement. From 2015 the capacity of nuclear technologies increases sharply reaching a maximum capacity of ~22GW by 2035. It is this increase in nuclear technologies that replaces some of the CCS in this scenario compared with Scenario A as well as some of the renewable technologies as we will see.

From 2015, there is growth in renewable technologies with on and offshore wind reaching a combined peak capacity of ~12GW in 2030. From 2030, there is growth in wave and tidal power technologies from 0GW in 2025 to ~15.5GW in 2050. Hydro technologies make a very similar contribution in this scenario as they do in the scenario A of ~4GW from 2020-2050. Biomass technologies also feature very strongly, contributing up to 18GW of capacity from 2025.

In summary, in the absence of the deployment of CCS technologies, nuclear technologies are more heavily relied upon, alongside, increased contributions from renewable technologies such as wave, tidal and biomass technologies with the continued presence of unabated gas until 2050 ~8GW; this equates to ~18-20GW in capacity. This is slightly more than the peak capacity of CCS in Scenario A which is

~15GW. This is because, apart from the nuclear technologies, all of the other technologies deployed are intermittent sources of power and so a greater capacity is required to ensure that demand is met as they are not base load technologies.

The results for Scenario B for electricity generation (see Figure 20) show that from 2000 until 2020 the UK's electricity generation is primarily made up of unabated gas (~146TWh in 2005 at its peak contribution) and unabated coal (~112TWh in 2005 at its peak contribution) with a significant contribution made by nuclear power (~78TWh in 2000 at its peak contribution).

From 2020, the proportional contribution of unabated coal and gas to UK electricity generation gradually declines as plants begin to retire. Similarly to Scenario A, they are not replaced due to the necessity to deploy low carbon technologies in order to meet the various emission constraints and carbon targets in the model. However, unlike Scenario A, in Scenario B, in the absence of CCS, unabated gas continues to make a contribution to electricity generation through until 2050 when it contributes ~27TWh of electricity.

In addition, onshore wind consistently generates ~19-22TWh of electricity from 2030, and offshore generates ~15TWh of electricity at its peak in 2030 which then declines gradually to ~3.5TWh in 2050. Wave and tidal technologies also make significant contributions, generating ~50TWh in 2050, up from ~17TWh in 2030. Biomass technologies also contribute strongly generating ~18TWh by 2050. The biggest contribution to generation is made by nuclear technologies. In 2015 they generate ~46TWh, equating to ~17% of total generation and this increases sharply until 2050 when the maximum generation is reached at ~164TWh; equating to ~55% of total generation (an increase of 5% versus Scenario A).

6.2.1.3 Scenarios A and B Diversity Profiles

In the same way that the electricity generation and the installed capacity results for Scenario A and B were presented the diversity profiles for both of these parameters are also presented. By looking at the profiles for installed capacity we can see how the diversity of the actual technologies built changes and by looking at the profiles for electricity generation we will be able to look at how the technologies built are used to generate electricity and how this affects the diversity of the system.

The diversity profiles for this thesis are presented using a moving average, a technique frequently applied to time series data to smooth out short term fluctuations and highlight longer term trends or cycles. In this thesis a 2 period moving average is used providing an average of the previous 2 data points. It is also important to point out that the absolute values for diversity are very low, as discussed in Chapter 5, and for comparative purposes, percentage changes from the baseline are quoted, which more accurately reflects actual changes in diversity.

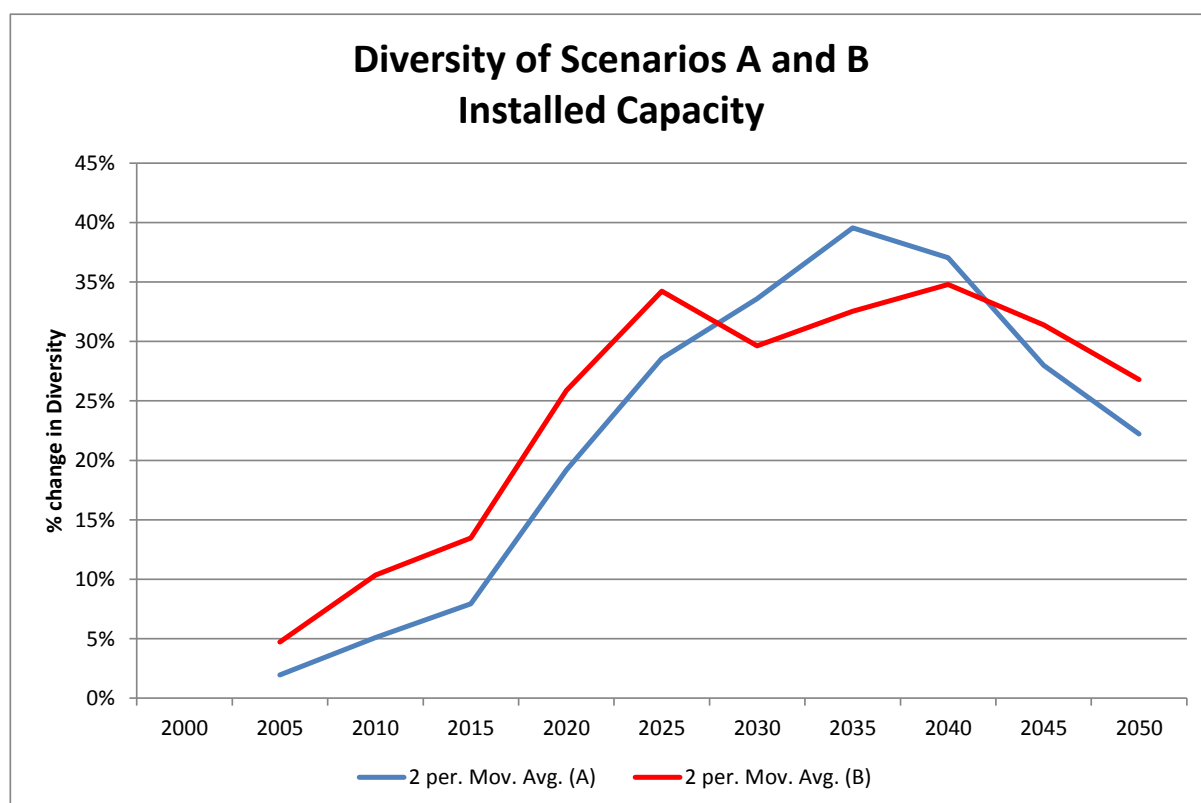
To begin with, the diversity profiles for the installed capacities of scenarios A and B (see Figure 21) have a number of differences despite the initial and final diversity values being the same³⁶. The profiles for both scenarios form sigmoidal curves, however, Scenario A (with CCS) forms a more defined curve with diversity gently increasing to a peak in 2035 (~40% increase in diversity compared to 2000) followed by a decline in diversity to ~22% above the baseline. This peak in diversity coincides with a middling deployment of CCS technologies (refer to Figure 19). In comparison, Scenario B has a very different shape with diversity rising to peak in 2025 (~36% increase in diversity compared to the baseline) and then again in 2040 (~31% increase in diversity compared to baseline) before declining to the same level of diversity as that of Scenario A.

The change in profiles over time clearly demonstrates that decarbonising the UK generating system under the assumptions used in the model will lead to an overall increase in diversity regardless of whether CCS technologies are deployed or not. Although the pattern of diversity between the two scenarios differs somewhat, the

³⁶ Absolute values for diversity for both scenarios is 0.0043 in 2000 and 0.00529 in 2050.

diversity at the end of both of the scenarios is comparable and the absolute values of diversity for both profiles converge in 2050 indicating that the system diversifies to the same point. Thus, the combination of the 80% climate target with certain policy instruments in place to promote low carbon generation may be responsible for this overall increase in diversity with or without the deployment of CCS technologies.

Figure 21 – Scenario A and B Diversity Profiles, Installed Capacity

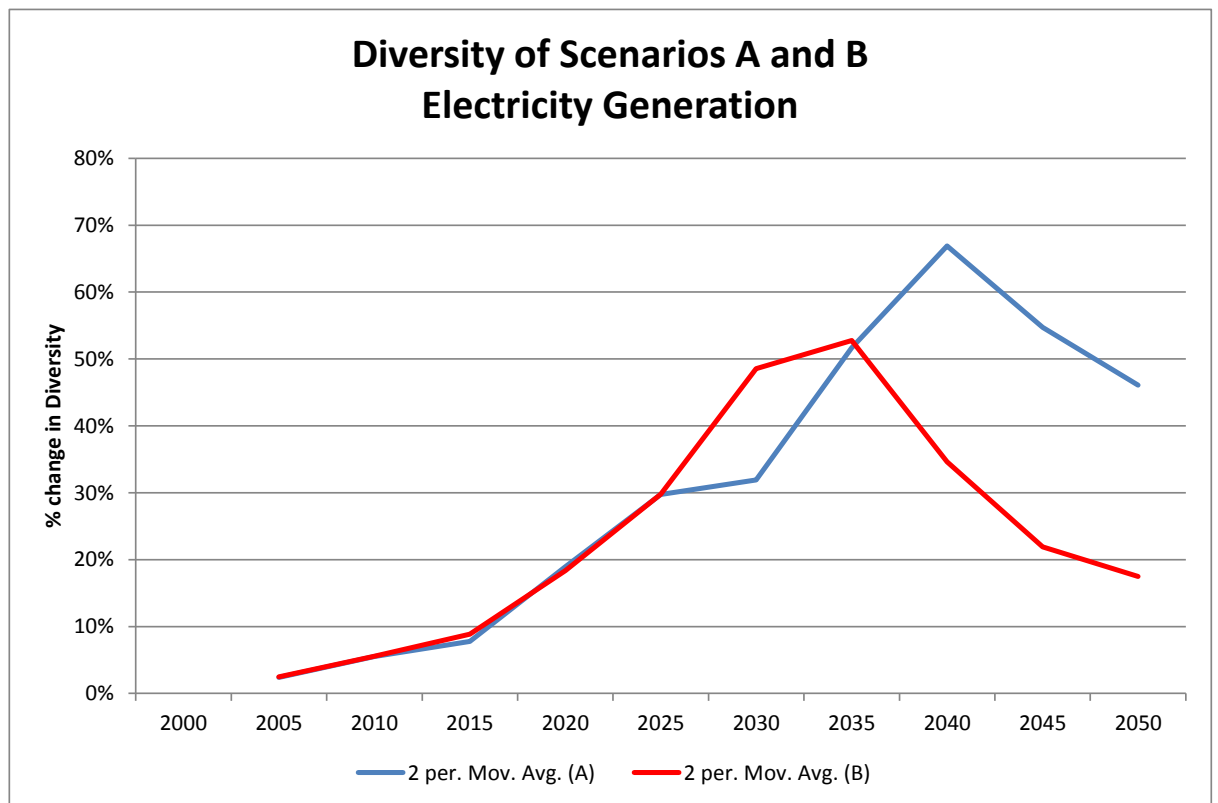


The diversity profiles for the electricity generation of Scenarios A and B are presented in Figure 22. Similarly to the diversity profiles for installed capacity, the profiles for electricity generation also form sigmoidal curves.

Both profiles follow similar trajectories until 2025 where they begin to diverge with a sharper increase in diversity in Scenario B, peaking in 2025 (~62% increase in diversity compared to 2000) and then declining rapidly to 2050 with an overall increase in diversity of ~17% versus the baseline. Scenario A increases in diversity steadily until 2040 (~70% increase in diversity compared to 2000) before declining, with an overall increase in diversity of ~46% versus baseline.

Although the diversity of generation under the two scenarios does not converge as closely in 2050 as it does for the diversity of installed capacity, nevertheless the results suggests that the system will diversify regardless of whether CCS technologies are deployed. This is an important result and will be returned to subsequently.

Figure 22 – Scenarios A and B Diversity Profiles, Electricity Generation



6.2.2 Capital Cost Scenarios

Three capital cost scenarios were run (see Figure 23). The results for each set of scenarios are collated (alongside Scenario A) for the installed capacity and electricity generation outputs in turn.

6.2.2.1 *Installed Capacity*

Each of the CCS Capital cost scenarios show unabated coal and gas dominating the electricity generation mix from 2000 to 2015 with peaks in capacity at 29GW and 25GW respectively. This largely reflects the current electricity mix in the UK. From 2015 there is considerable growth in on and offshore wind technologies reaching peak capacities of ~9GW and ~4GW respectively in each of the scenarios. Tidal and Wave Power also enter the system in each of the scenarios from approx. 2030 reaching an installed capacity of ~10-11GW by 2050.

Nuclear power is also an important technology to consider, featuring very strongly in generating electricity for the system as was the case in the reference scenario. Nuclear technologies start relatively strongly in 2000 through until 2010 when their decline coincides with a large degree of retirement of the UK's nuclear fleet falling to just 5-6GW of capacity in 2020. Nuclear power then starts to grow in each of the scenarios. When the capital costs of CCS technologies are at their lowest then the model builds this in favour of nuclear technologies (see Figure 23). However, as the capital costs for CCS technologies rises throughout each of the scenarios and the capacity of nuclear technologies built increases, the capacity of CCS technologies decreases as they become less cost-effective for deployment by the model. This is also accompanied by the existence of a 'fuel price drag' associated with CCS technologies. More specifically, the cost of fuel i.e. fossil fuels, also contributes towards the cost of CCS technologies making them even more costly than technologies such as onshore wind technologies, which has no associated fuel costs.

With regards to the CCS technologies, as you would expect from a cost-optimisation model, the capacity of CCS technologies built declines with increasing capital costs. With a more specific focus on the CCS technologies themselves, it is clear from the graphs that the model builds more gas CCS as opposed to coal CCS. This is because the

capital costs for CCS plants are generally the lower of the two, however, as we will see for electricity generation, the model chooses coal CCS for electricity generation over gas CCS due to lower costs of carbon abatement of coal versus gas.

The diversity profiles generated for this set of scenarios are presented in Figure 24. Each of the scenarios follows a similar trajectory to Scenario A, (discussed in more detail in section 6.2.1.3) until 2025. The high scenario continues to increase in diversity until 2050 with an overall increase in diversity of ~32% versus the baseline. The high-high scenario however, peaks in 2025 with an increase of ~27% in diversity versus the baseline and then plateaus. In contrast the low scenario peaks in diversity in 2020 (a ~17% increase in diversity versus the baseline) and then declines in diversity until 2035 (a ~18% decrease in diversity versus the baseline) when the profile then flattens out.

The reason for the differences seen in these profiles is because when CCS costs are at their lowest then this makes the technology a more-cost optimal solution for the model and so it builds as much CCS technology as possible within the constraints of the model. As a result, the diversity of the scenario remains very low and even falls as the capacity of CCS technology rises above 25GW. In contrast, as CCS capital costs rise and other technologies become more optimal solutions for the model then as the capacity of CCS falls, the diversity of the scenarios increases.

However, regardless of the difference in CCS capital costs in the scenarios the system still diversifies with a general overall increase in diversity between 2000 and 2050.

Figure 23 – CCS Capital Cost Scenarios – Installed Capacity

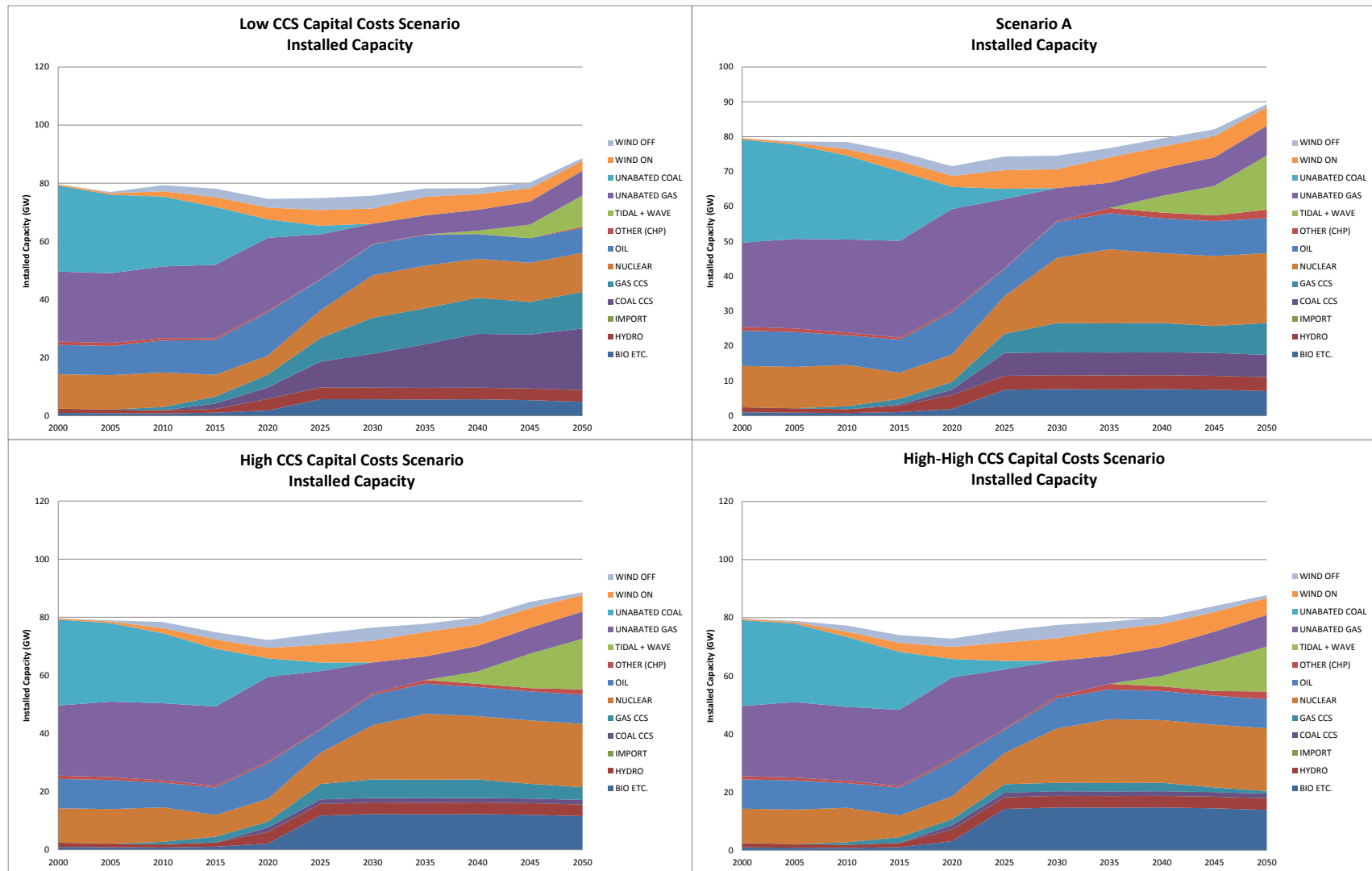
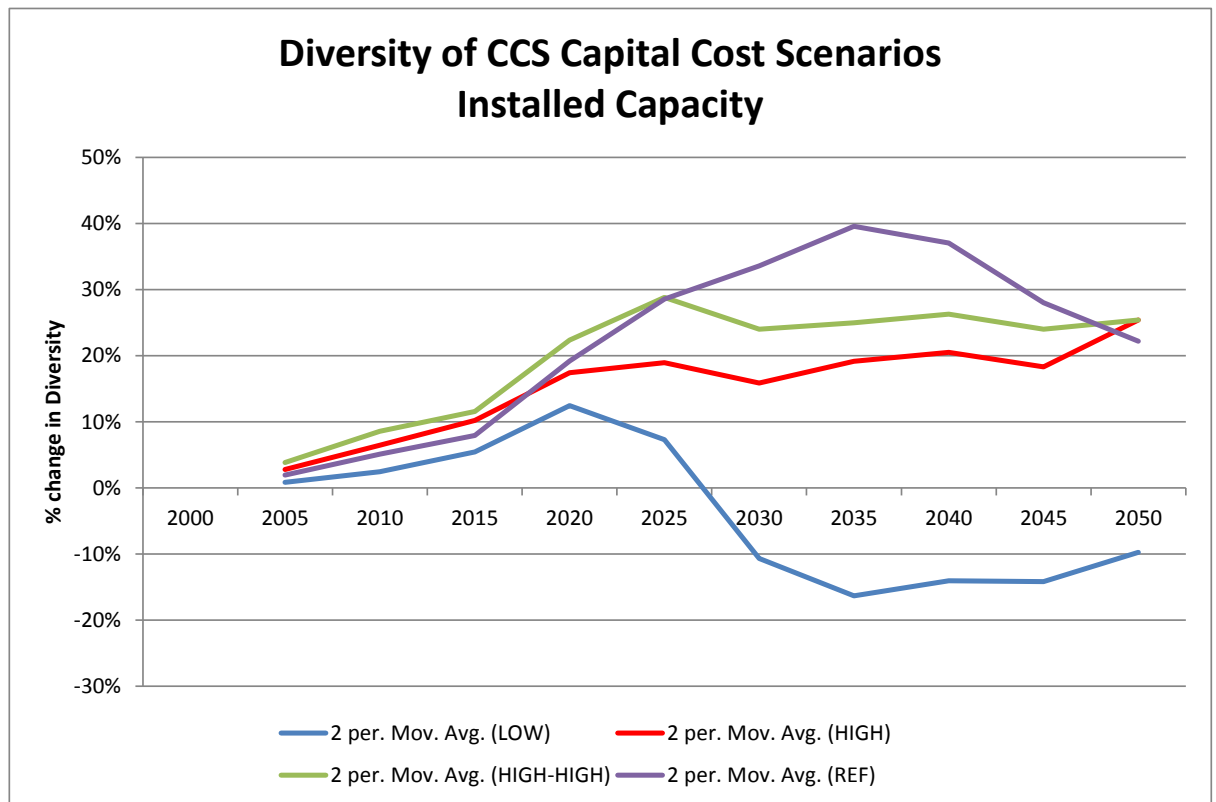


Figure 24 – Summary of Diversity Profiles for CCS Capital Cost Scenarios, Installed Capacity



Notes –Scenario A is shown in black, the low scenario profile in blue, the central scenario in red, the high scenario in green and the high-high scenario in purple.

6.2.2.2 Electricity Generation

Each of the scenarios for the electricity generation results shows that from 2000 until 2020 the UK's electricity generation is primarily made up of unabated gas (~146TWh in 2005 at its peak contribution) and unabated coal (~112TWh in 2005 at its peak contribution) with a significant contribution made by nuclear (~78TWh in 2000 at its peak contribution). From 2000 until 2020 the proportional contribution of unabated gas and coal to UK electricity generation steeply declines to 116TWh and 43TWh respectively.

The decline in unabated gas and coal electricity generation is accompanied by a growth in the contribution of on and offshore wind technologies with peak contributions of ~22TWh and ~9TWh respectively. There is also an increasing contribution of Tidal and Wave Power of ~34-37TWh by 2050 in the high and high-high scenario contributing ~72TWh to total installed capacity.

Nuclear generation also plays a significant role in each of these scenarios. As the capital costs for CCS technologies rise and the Levelised Cost of Electricity³⁷ (LCOE) for CCS technologies rises then the contribution of nuclear generation in the mix also rises. In the low capital cost scenario, coal and gas CCS generation dominate the mix contributing ~135TWh towards total electricity generation in 2050. However, in the high-high CCS capital cost scenario, nuclear power makes its most substantial contribution to system electricity generation of ~150TWh in 2050. This is because of the low capital costs of CCS technologies which in addition to the 'fuel price drag' that they experience are still more cost-effective than nuclear generation. However as the capital costs of CCS technologies rises, nuclear generation, as we have seen, becomes the favoured technology by the model.

We have discussed and compared the electricity generation results for the CCS capital cost scenarios. To gain a better picture of the influence of varying CCS capital costs on each of the scenarios it is useful to compare how the electricity generation mix of these technologies changes across the scenarios and then to explore the diversity profiles of the scenarios, the next stage of the analysis.

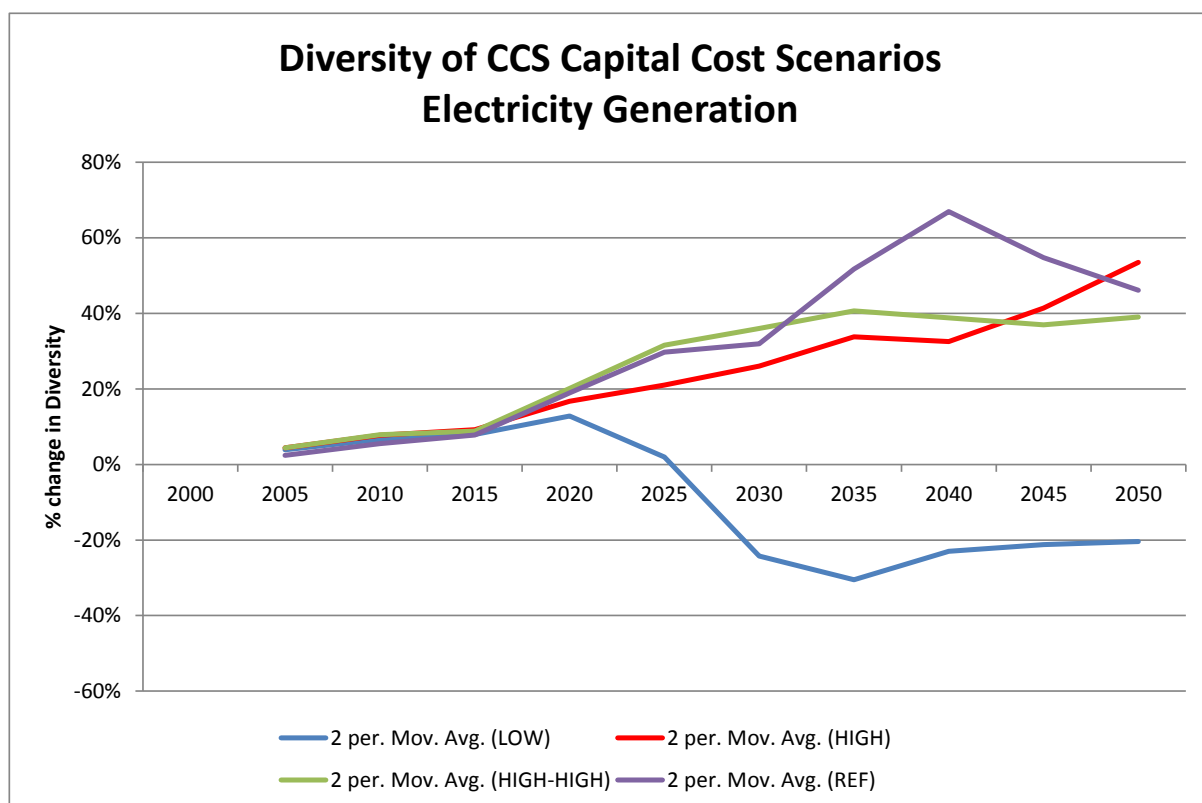
³⁷ Levelised Cost of Electricity refers to the price at which electricity must be generated from a specific source to break even over the lifetime of a project.

The diversity profiles of these scenarios are presented in Figure 25, the profiles for the CCS capital cost rate scenarios are the same until 2015 where they start to diverge. The high and high-high profiles continue to increase in diversity of ~54% and ~42% respectively, versus the baseline, however, the low scenario sees a decrease in diversity of ~37% versus baseline at its lowest point. From 2035, the low scenario does increase in diversity slightly, but does not reach the baseline level of diversity again in this scenario.

The increases in diversity across the scenarios in general (except the low scenario) can be explained by the increases in CCS capital costs making CCS technologies no longer the most cost-optimal solution for the model. As a result, the model uses alternative more cost-optimal technologies to generate electricity, reflected in the overall rise in profile diversity. In contrast, when CCS capital costs are more cost-optimal and are deployed, there will be a greater reliance on fewer technologies for generation leading to a decrease in the diversity of the generation technologies in the scenario.

Interestingly, unlike the profiles for the installed capacity where the diversity of the scenarios at the start and end-points of the scenarios are very similar there is overall a general increase in the diversity of generation from 2000 to 2050 (apart from the low scenario).

Figure 25 – Summary of Diversity Profiles for CCS Capital Cost Scenarios, Electricity Generation



Notes – Scenario A is shown in black, the low scenario profile in blue, the central scenario in red, the high scenario in green and the high-high scenario in purple.

Figure 26 – CCS Capital Costs Scenario – Electricity Generation



6.2.3 Fossil Fuel Price Scenarios

Three fossil fuel price scenarios were run (see Table 15 and Table 16 for assumptions and constraints). The results for each set of scenarios are presented collated for the installed capacity and electricity generation outputs in turn.

6.2.3.1 *Installed Capacity*

Each of the fossil fuel price scenarios (see Figure 27) show unabated coal and gas dominate the electricity generation mix from 2000 to 2015 with peaks in capacity at 29GW and 25GW respectively; accurately reflecting the current electricity mix in the UK at present. From 2015, there is considerable growth in on and offshore wind technologies reaching peak capacities of ~9GW and ~4GW respectively in each of the scenarios. Tidal and Wave Power also enter the system in each of the scenarios from approx. 2030 reaching an installed capacity of ~10-11GW by 2050.

Nuclear power also features very strongly in generating electricity for the system as was the case in the Scenario A. Nuclear technologies start relatively strongly in 2000 through until 2010 when their decline coincides with a large degree of retirement of the UK's nuclear fleet falling to just 7-8GW of capacity in 2015. Nuclear power then starts to grow in each of the scenarios. When fossil fuel prices are at their lowest then the model builds up to 23GW of CCS technology. As the price of fossil fuels increase and the 'fuel price drag' becomes more applicable, then the capacity of CCS technologies in the high and high-high scenarios falls to ~13GW and ~7GW respectively in 2050. As this happens the model opts to build nuclear technologies instead, as they prove a more cost effective solution, as we have seen in other scenarios. In the high and high-high fossil fuel price scenarios, the capacity of nuclear technologies reaches 21GW and 26GW respectively compared to just 8GW in the low fossil fuel price scenario.

With a more specific focus on the CCS technologies, it is clear from the graphs that the model builds more gas CCS as opposed to coal CCS and this is because the capital costs for CCS plants are generally the lower of the two. However, as we will see for electricity generation, the model chooses coal CCS for electricity generation over gas CCS due to lower costs of carbon abatement of coal versus gas.

We have discussed and compared the installed capacity results for the fossil fuel price scenarios. The diversity profiles generated for this set of scenarios are presented in Figure 28. Each of the scenarios has the same diversity profile until 2015-2020 when they start to diverge. Each of the profiles is less diverse than the reference profile, with the low fossil fuel price scenario being the least diverse profile. The low scenario peaks in diversity in 2025, an increase in diversity of ~21% compared to the baseline, which then decreases ~10%. The high and high-high scenarios increase in diversity ~36% and ~42% respectively compared to the baseline but then decline by ~12% and 15% respectively.

The reasons for these changes are that when fossil fuel prices are low and the associated technologies are heavily relied upon then there is less investment into alternatives which keeps the diversity low. As fossil fuel prices increase and non-fossil fuel technologies receive investment and are deployed, then the diversity of the generating system will increase. This is reflected in the results discussed above.

To gain a better picture of the influence of varying fossil fuel prices on each of the scenarios it is useful to compare how the electricity generation mix of these technologies changes across the scenarios and then to explore the diversity profiles of the scenarios, the next stage of the analysis.

Figure 27 – Fossil Fuel Price Scenarios – Installed Capacity

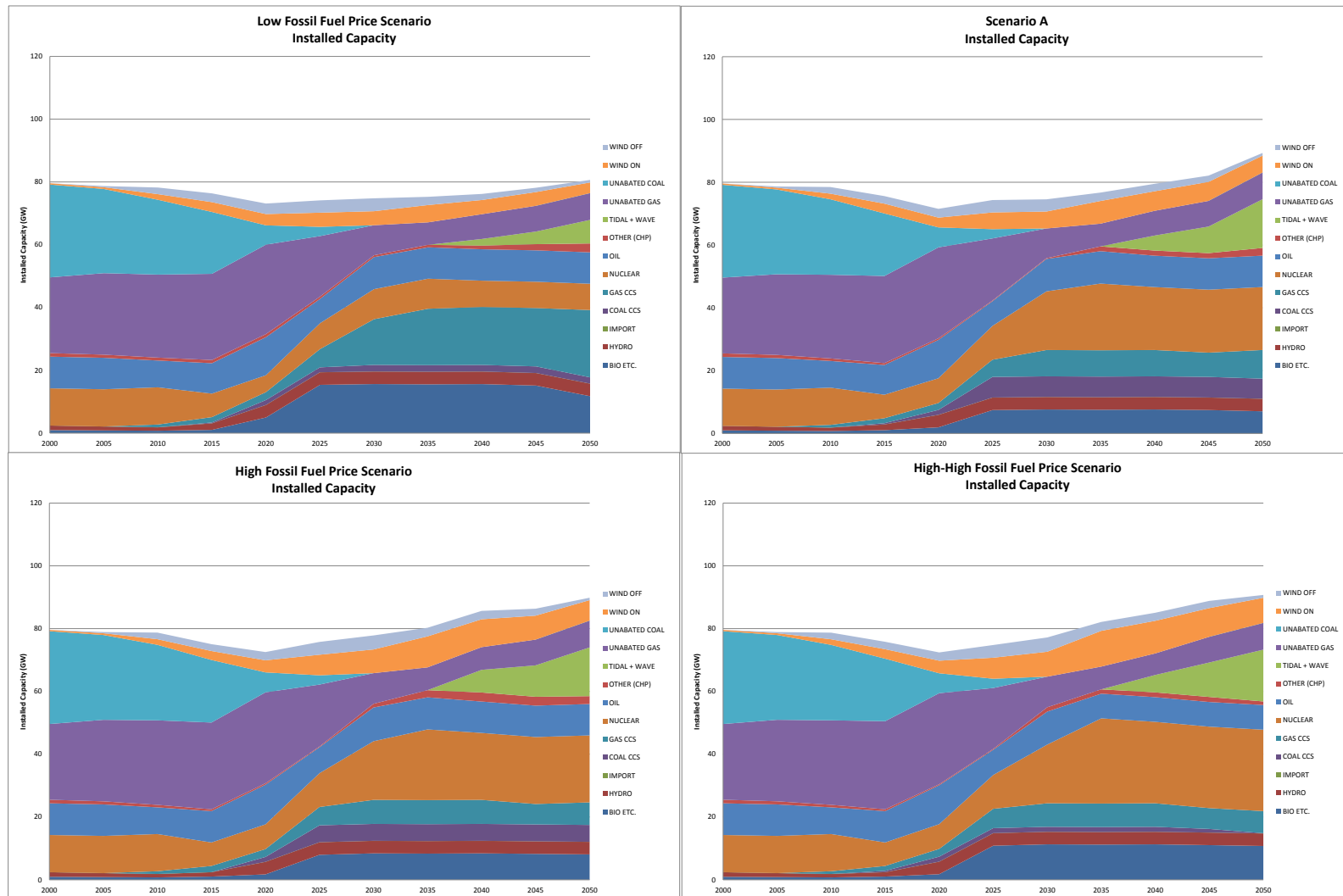
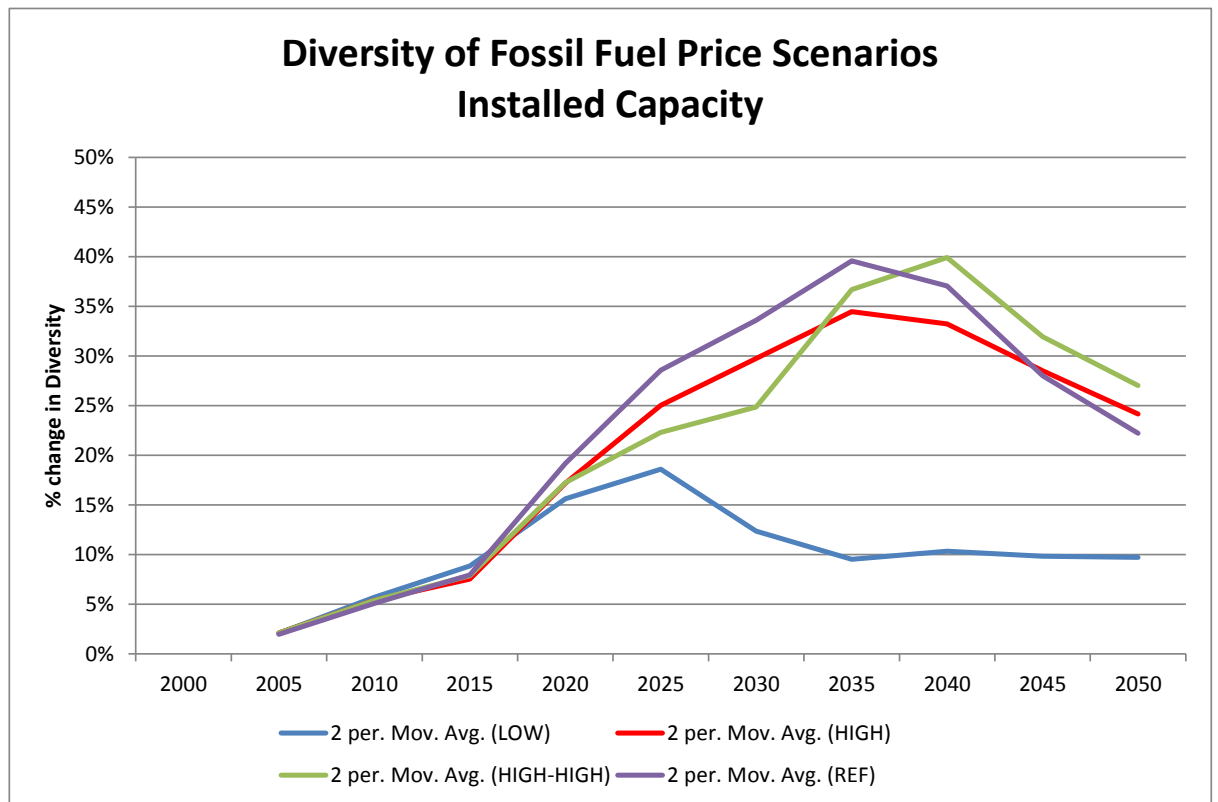


Figure 28 – Summary of Diversity Profiles for Fossil Fuel Price Scenarios



Notes– Scenario A is shown in black, the low scenario profile in blue, the central scenario in red, the high scenario in green and the high-high scenario in purple.

6.2.3.2 Electricity Generation

Each of the scenarios for the fossil fuel price assumptions for electricity generation, shows that from 2000 until 2020 the UK's electricity generation is primarily made up of unabated gas (~135TWh in 2005 at its peak contribution) and unabated coal (~112TWh in 2005 at its peak contribution) with a significant contribution made by nuclear (~78TWh in 2000 at its peak contribution). From 2000 until 2030, the proportional contributions of unabated gas and coal to UK electricity generation start to decline across scenarios as the UK's existing fleets start to retire. In response, there is significant growth in the contribution of onshore and offshore wind technologies with peak contributions in 2035 and 2030 respectively of ~23TWh and ~13TWh in the high-high scenario. Tidal and Wave Power also makes an increasing contribution peaking in 2050 at ~37TWh.

Nuclear generation also plays a significant role in each of these scenarios. As the capital costs for CCS technologies rise and the LCOE for CCS technologies rises then the contribution of nuclear generation in the mix also rises. In the low capital cost scenario coal and gas CCS generation dominate the mix contributing ~135TWh towards total electricity generation in 2050. However, in the high-high CCS capital cost scenario, nuclear power makes its most substantial contribution to system electricity generation of ~150TWh in 2050. This is because of the low capital costs of CCS technologies which, in addition to the 'fuel price drag' they experience, are still more cost-effective than nuclear generation. However, as the capital costs of CCS technologies rise, nuclear generation as we have seen becomes the favoured technology by the model.

We have discussed and compared the electricity generation results for the fossil fuel price scenarios. To gain a better picture of the influence of varying fossil fuel prices on each of the scenarios it is useful to compare how the electricity generation mix of these technologies changes across the scenarios and then to explore the diversity profiles of the scenarios, the next stage of the analysis.

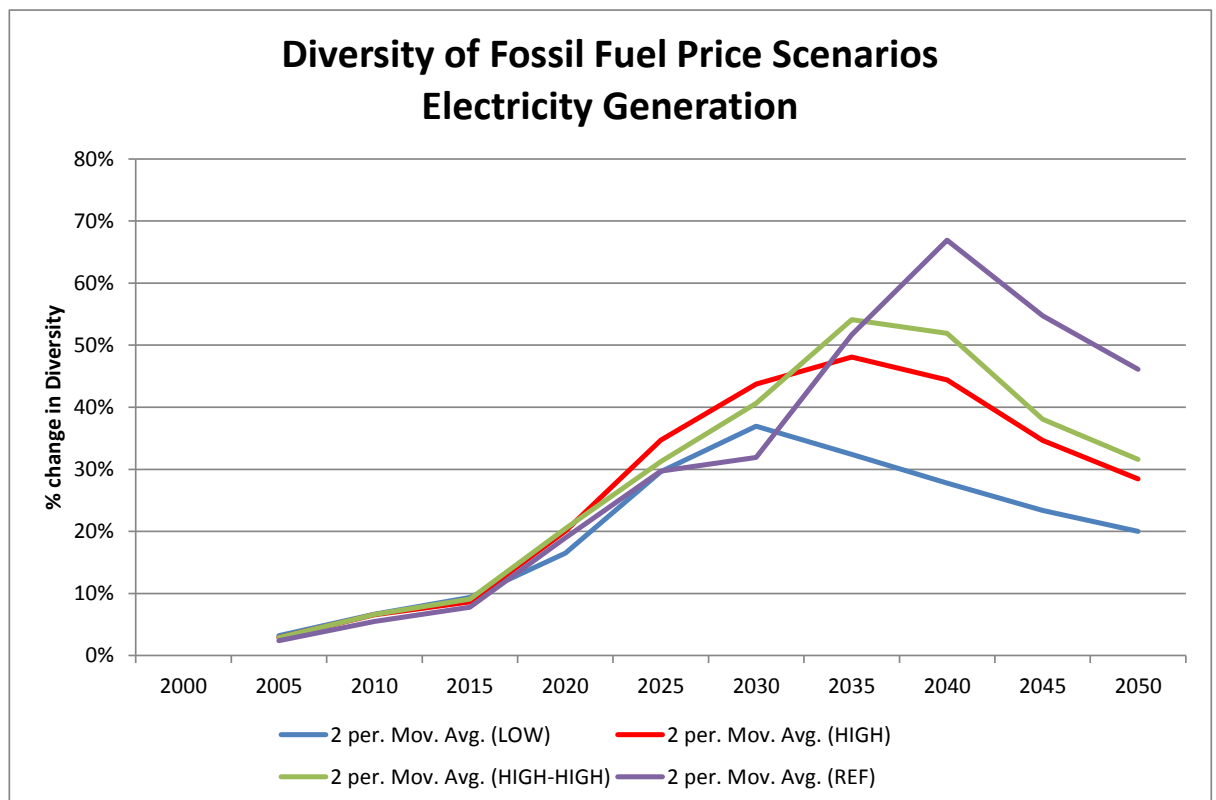
The diversity profiles of these scenarios are presented in Figure 29, the profiles for the fossil fuel price scenarios are very similar until 2015 where they start to diverge. Each

of the scenarios is more diverse until 2035 than Scenario A with a peak in diversity of ~38% above baseline for the low scenario, ~49% for the high scenario and ~59% for the high-high scenario. However, compared to Scenario A each of the scenario profiles for electricity generation is less diverse.

The low fossil fuel price scenario has the least diverse profile because in this scenario there is a strong reliance on fossil fuel technologies for generation. This is the same as the results we saw in the installed capacity results where a low fossil fuel price resulted in less investment into non-fossil fuel technologies also leading to a less diverse profile for this scenario.

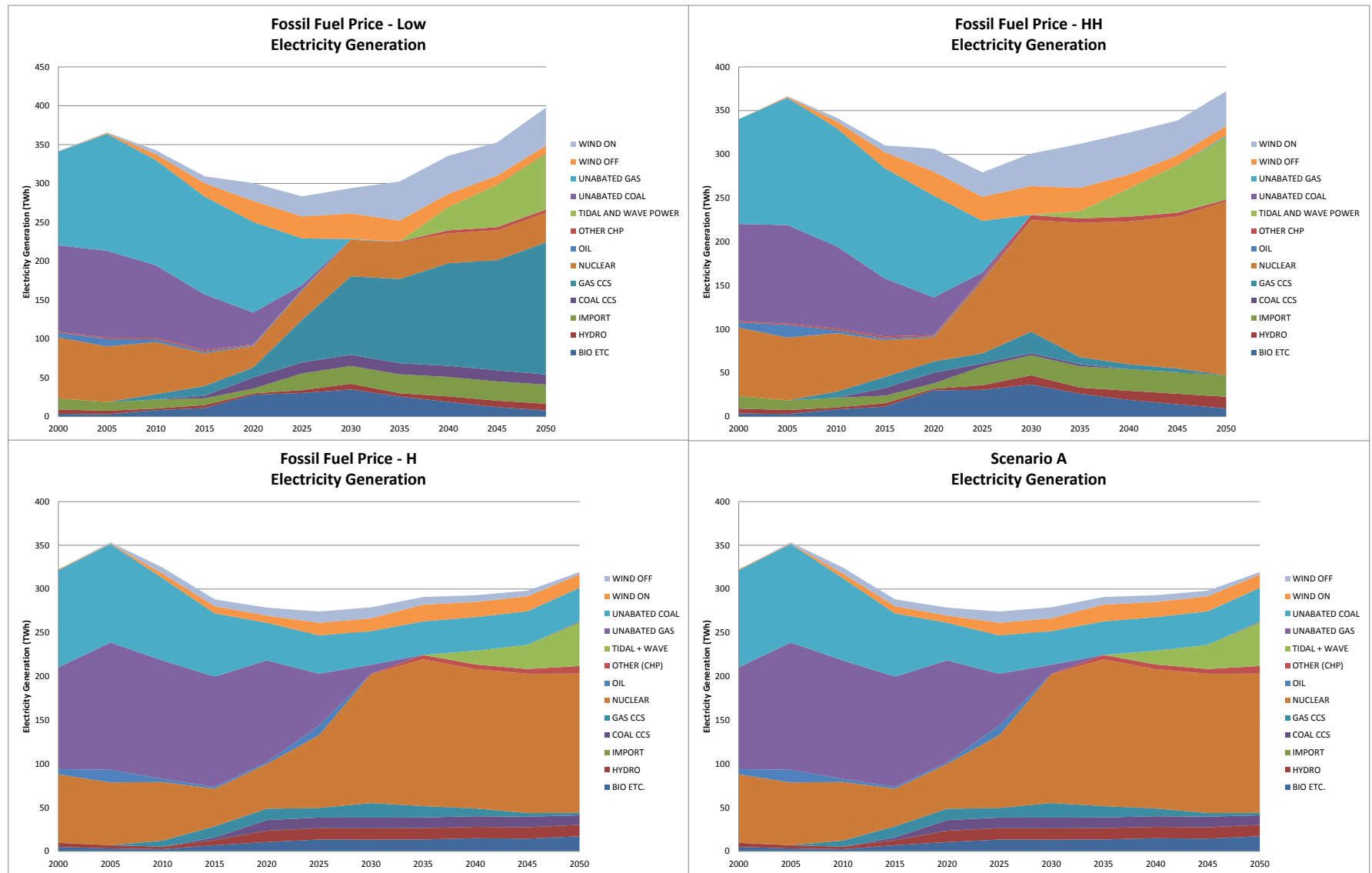
In the same way the inverse occurs with the high and high-high profiles resulting in profiles that are more diverse than the low scenario.

Figure 29 – Summary of Diversity Profiles for fossil fuel price scenarios - electricity generation results



Notes – Scenario A is shown in black, the low scenario profile in blue, the central scenario in red, the high scenario in green and the high-high scenario in purple.

Figure 30 – Fossil Fuel Price Scenarios – Electricity Generation



6.2.4 Build Rate Scenario Results

Three CCS build rate scenarios were run (see Table 15 and Table 16 for details of assumptions and constraints applied). The result for each set of scenarios is collated for the installed capacity and electricity generation outputs in turn.

6.2.4.1 Installed Capacity

Each of the CCS build rate scenarios (see Figure 32) show unabated coal and gas dominates the electricity capacity from 2000 to 2015 with peaks in capacity at 29GW and 25GW respectively. This accurately reflects the current situation in the UK at present. From 2015, there is considerable growth in on and offshore wind technologies reaching peak capacities of ~9GW and ~4GW respectively in each of the scenarios. Tidal and Wave Power also enters the system in each of the scenarios from ~ 2030 reaching an installed capacity of ~10-11GW by 2050.

Nuclear power is also an important technology to consider because it also features very strongly in generating electricity for the system as was the case in the Scenario A. Nuclear technologies start relatively strongly in 2000 through until 2010 when their decline -coincides with a large degree of retirement of the UK's nuclear fleet falling to just 7-8GW of capacity in 2020. Nuclear power then starts to grow in each of the scenarios reaching capacities of 30-31GW across all of the scenarios. When the build rates of CCS technologies are at their lowest then the capacities of other generation technologies increases, particularly biomass technologies which have a peak capacity of just 3GW in the high-high scenario compared with 10GW in the low scenario. Other technologies such as on and offshore wind generation technologies fluctuate in their capacities but these are fairly similar across scenarios.

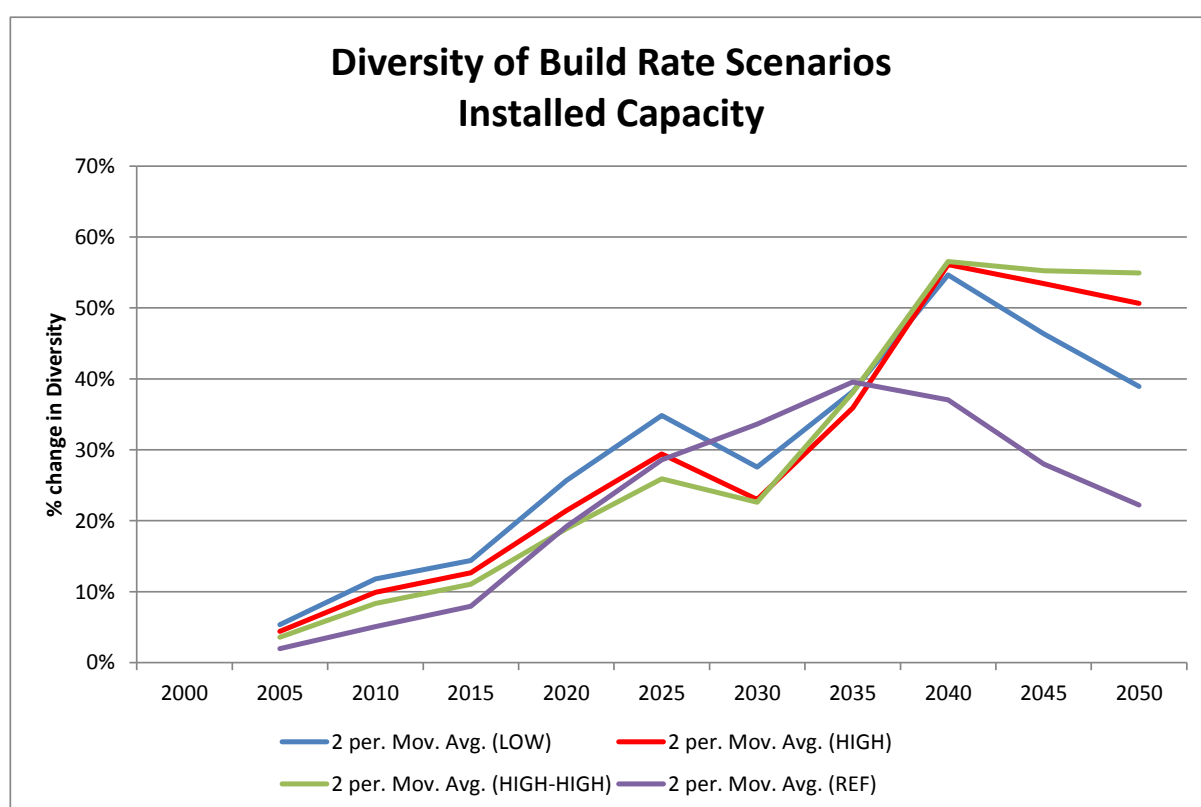
With a more specific focus on the CCS technologies, it is clear from the graphs that the model builds more gas CCS as opposed to coal CCS and this is because the capital costs for CCS plants are generally the lower of the two. However, as we will see for electricity generation, the model chooses coal CCS for electricity generation over gas CCS due to lower costs of carbon abatement of coal versus gas.

The diversity profiles generated for this set of scenarios are presented in Figure 31. The diversity profiles for the build rate scenarios follow a very similar trajectory for

Scenario A in 2025, although all three scenarios are more diverse. From 2020 the diversity of these three scenarios falls to form a trough before increasing once again to peak in 2040. Meanwhile Scenario A continues to increase in diversity until 2035 where it peaks and plateaus. The increase in diversity for the low, high and high-high scenarios versus the baseline are ~55%, ~56% and ~57% respectively. As the build rate for CCS technologies increases, there is an overall increase in the diversity of the scenario. This is because as the build rate is increased the model has the option to build more and more CCS technologies if this is the most-effective solution. As it does so the diversity of the scenario increases.

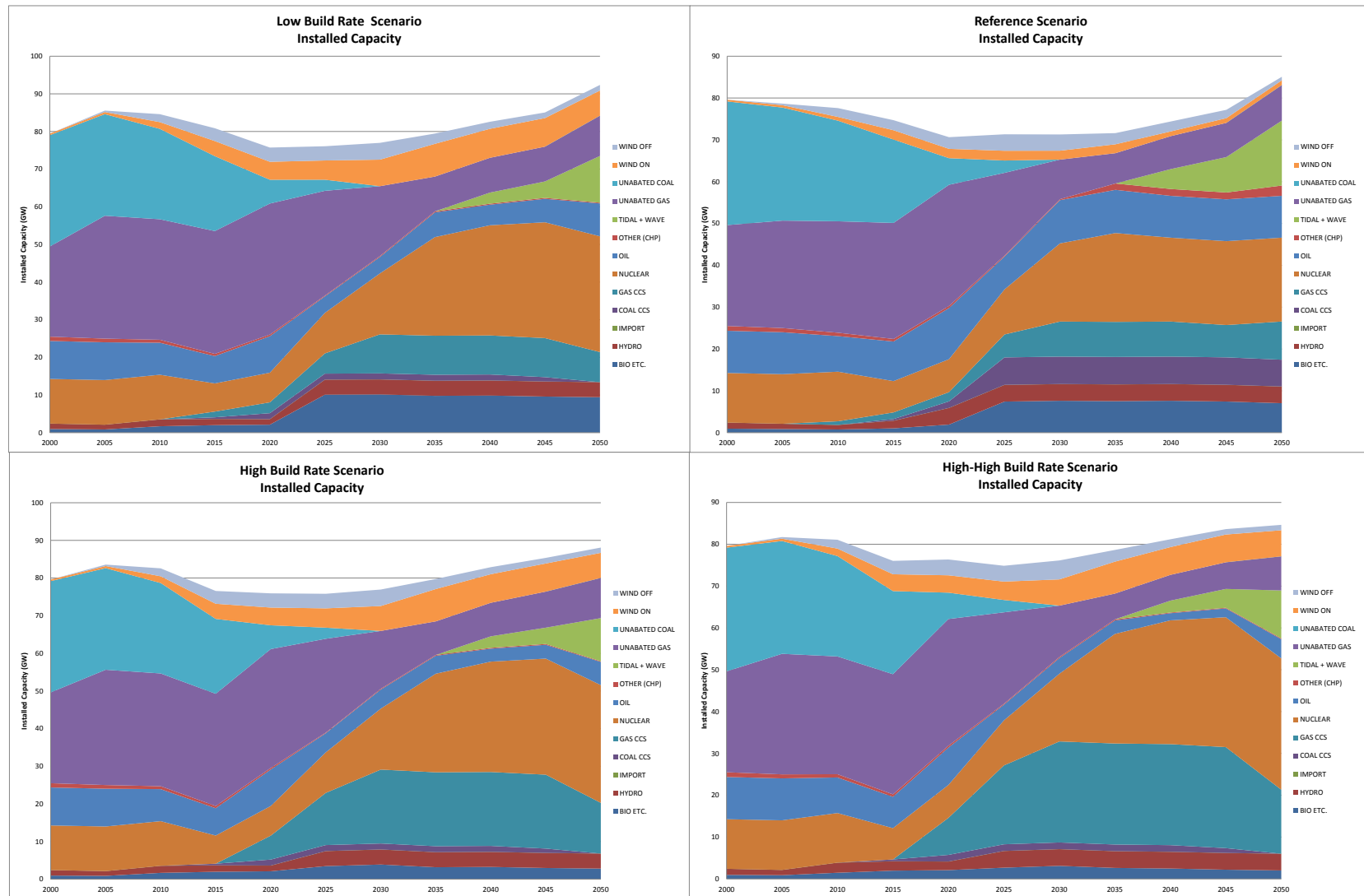
To gain a better picture of the influence of varying CCS build rates on each of the scenarios it is useful to compare the diversity profiles of each of the scenarios, the next stage of the analysis.

Figure 31 - Summary of Diversity Profiles for CCS Capital Cost Scenarios



Notes – the reference scenario (with CCS) profile is shown in black and the build rate profile in blue.

Figure 32 – CCS Build Rate Scenarios – Installed Capacity



6.2.4.2 Electricity Generation

Each of the scenarios for the fossil fuel price assumptions for electricity generation show that from 2000 until 2020 the UK's electricity generation is primarily made up of unabated gas (~135TWh in 2005 at its peak contribution) and unabated coal (~112TWh in 2005 at its peak contribution) with a significant contribution made by nuclear (~78TWh in 2000 at its peak contribution). From 2000 until 2030 the proportional contributions of unabated gas and coal to UK electricity generation start to decline across scenarios as the UK's existing fleets begin to retire. In response, there is significant growth in the contribution of onshore and offshore wind technologies to the mix with peak contributions in 2035 and 2030 respectively at ~14TWh and ~9TWh in the high-high scenario. Tidal and Wave Power also makes a significant increasing contribution towards the end of the scenario contributing ~36TWh by 2050.

Nuclear generation also plays a significant role in each of these scenarios. Despite the CCS build rate raising through the scenarios the contribution of nuclear to the generating mix remains very high throughout. In the low CCS build rate scenarios this is because of the restricted build rate of CCS technologies and so nuclear becomes necessary to meet demand. As the capacity of CCS technologies increases, nuclear still remains the stronger contributor to the generation mix. This is because it is the more cost-effective option for the model as discussed in earlier scenarios.

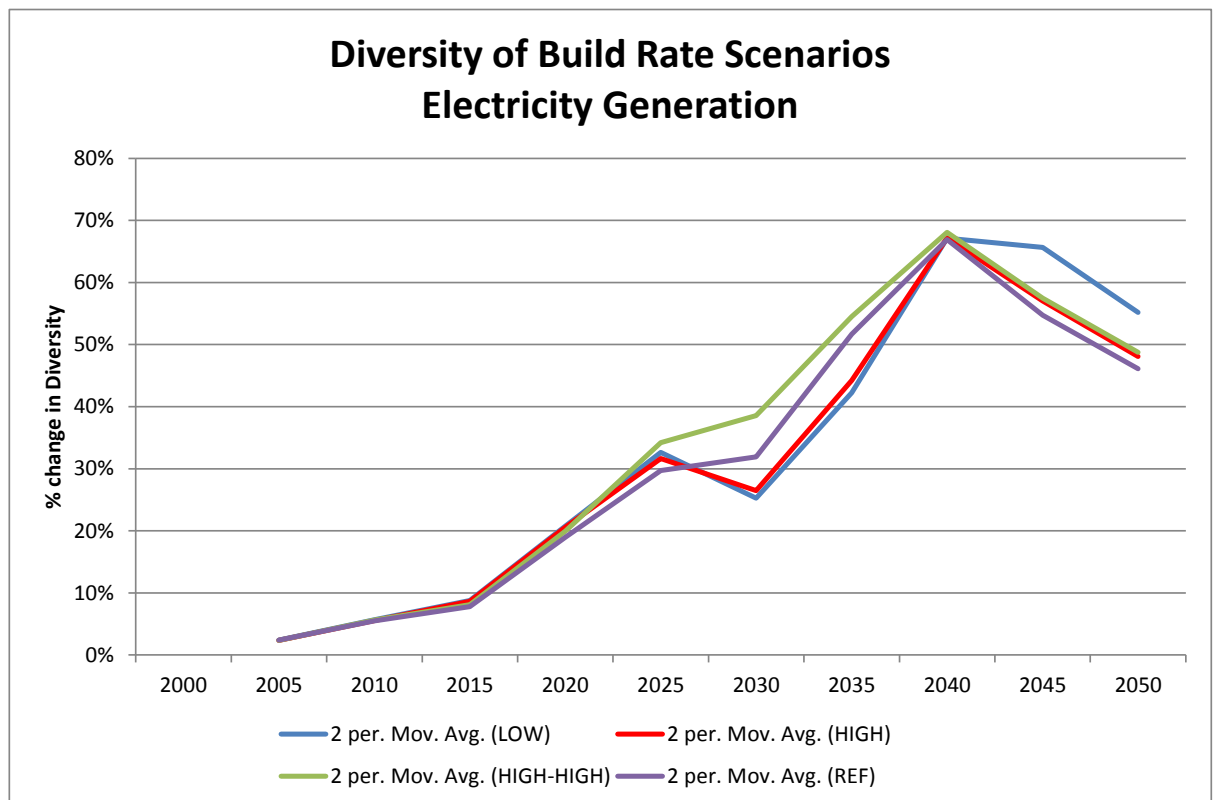
We have discussed and compared the electricity generation results for the CCS build rate scenarios. To gain a better picture of the influence of varying fossil fuel prices on each of the scenarios it is useful to compare how the electricity generation mix of these technologies changes across the scenarios and then to explore the diversity profiles of the scenarios.

The diversity profiles of these scenarios are presented in Figure 33, the profiles for the CCS build rate scenarios are very similar to Scenario A until 2025 with the low scenario peaking in diversity at ~35% versus baseline, the high scenario at ~33% versus baseline and the high-high scenario at ~38% versus baseline. The scenarios then diverge with the low and high scenarios experiencing small decreases in diversity followed by a sharp increase to converge with the high-high scenario in 2040. In 2040 the increase in

diversity of each of the scenarios versus the baseline is ~66%. This is followed by a fall in diversity to 2050 by ~20% versus baseline.

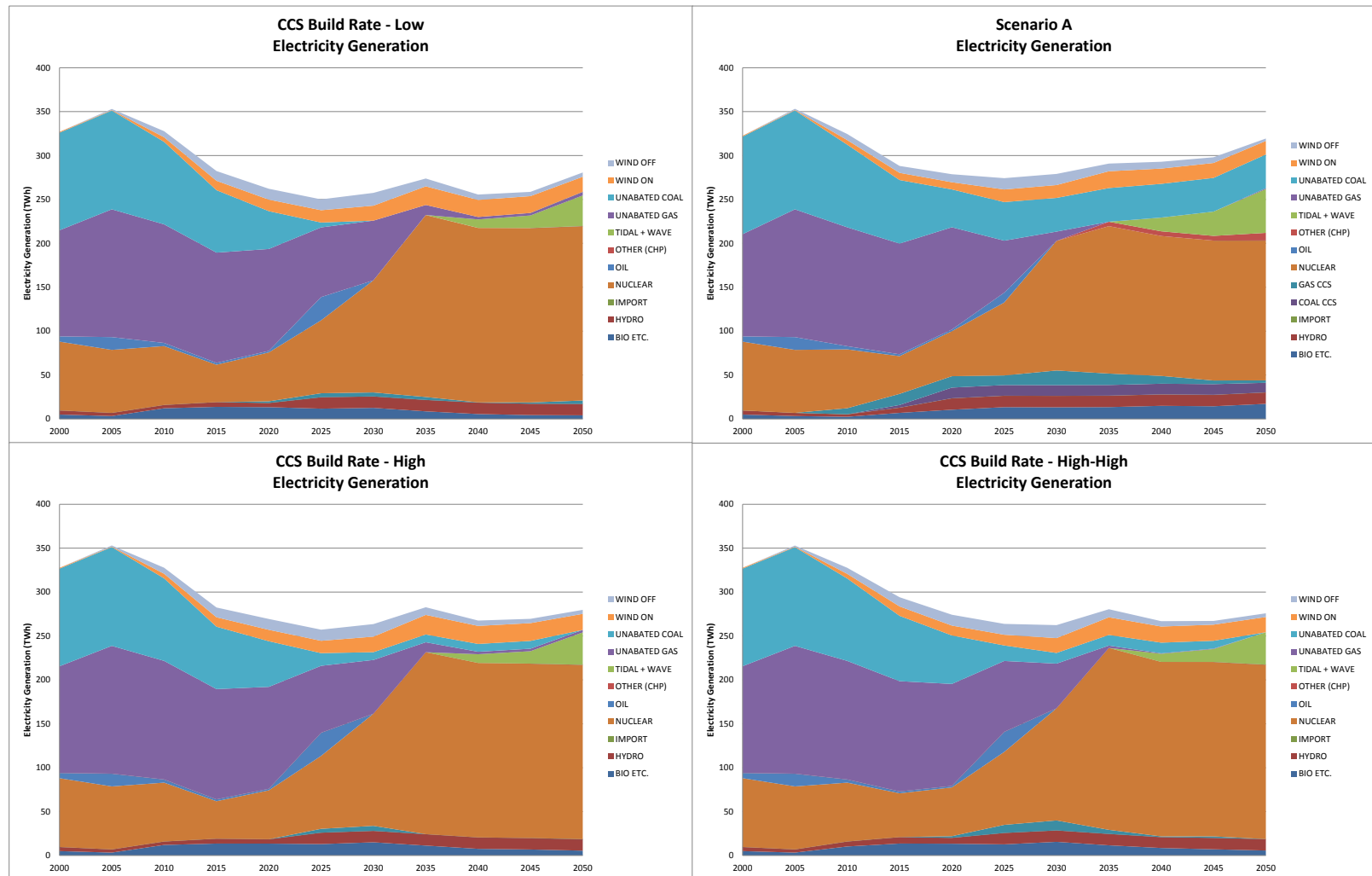
The divergence of the high-high profile is due to the increase in diversity of the generating mix of technologies as discussed in the results for the installed capacity. As a result the model has more options available to it for generation and so in this instance a more diverse mix is more cost-effective for this scenario.

Figure 33 - Summary of Diversity Profiles for the CCS build rate scenarios



Notes – Scenario A is shown in black, the low scenario profile in blue, the central scenario in red, the high scenario in green and the high-high scenario in purple.

Figure 34 – CCS Build Rate Scenarios – Electricity Generation



6.2.5 Results Summary

This chapter has provided a detailed analysis of the scenarios generated for this thesis using MARKAL. Four different input assumptions were varied in a number of ways to enable the effect of each parameter on the deployment of CCS technologies and their subsequent contributions to electricity generation to be made. In addition to this the diversity profile for each scenario and their corresponding results was presented.

The next part of the empirical analysis will take the results of the stakeholder interviews and analyse the subsequently generated disparity matrices. These matrices will then be used to generate further diversity profiles for each scenario to enable comparison and enable each stakeholder's perspectives in the partitioning of energy options to be derived.

CHAPTER 7. Empirical Analysis II

7.1 Chapter Introduction

This is the second of two empirical chapters which contains the results of stakeholder interviews used to generate ‘individualised’ disparity matrices to help answer research question 3. These are then subsequently used to generate further diversity profiles for each scenario for comparison. This process will enable each individual’s perspectives on the partitioning of energy options to be derived from the technologies incorporated into MARKAL.

7.2 Scenario Diversity Analysis with Stakeholder Appraisal of Performance Data

This objective of this next section is to present a detailed analysis of the diversity of the scenarios, but this time with the addition of a stakeholder appraisal of the MARKAL performance data used to subsequently quantify disparity. The diversity for each scenario is determined using Stirling’s heuristic as described in Chapter 5 and a diversity profile generated for each scenario as in the previous chapter. This time however, values for disparity specific to individual stakeholder’s perspectives on ‘*how disparate technologies are from one another*’ are incorporated into the calculation of the heuristic.

7.2.1 Stakeholder Appraisal of Performance Data

As discussed in more detail in Chapter 5, 12 stakeholders were each asked to appraise the technology performance data in MARKAL and then score each of these criteria making up the performance data between 0 and 100 according to their importance in addressing the questions ‘*how disparate are technologies from one another*’.

The results of this exercise are presented in Table 18. It is clear from the values assigned for each criterion that different individual stakeholders can have very different perceptions. For example, criterion 1 (availability factor) receives a score of just 20 by one participant (SPA5), indicating that this participant does not perceive this

criterion to be of high relative importance in determining how disparate technologies are from one another. In contrast another participant (SPA1) scores this same criterion with a value of 100 indicating that they perceive this criterion to be highly important in determining how disparate individual technologies are from one another. This variation in scoring between interview participants can be seen across all of the criteria indicating that interview participants have divergent views on the relative importance that different criteria have in determining how disparate technologies are from one another.

Table 18 – stakeholder scoring for each criterion of the performance data

Interviewee	Availability Factor	Electrical Efficiency	Capital Costs	Fixed O&M Costs	Variable O&M Costs	Plant Lifetime	Cont. to peak load
SPA1	100	50	100	100	100	50	50
SPA2	98	60	60	50	50	60	90
SPA3	65	70	90	75	80	55	60
SPA4	50	30	60	20	40	30	30
SPA5	20	20	60	20	60	20	20
SPA6	80	60	20	30	40	30	80
SPA7	80	20	60	70	70	0	0
SPA8	70	10	40	20	70	60	70
SPA9	40	Ren – 0 Nu – 25 FF - 60	65	40	40	60	10
SPA10	90	100	100	Ren – 0 Nu – 60 FF - 50	Ren – 0 Nu – 60 FF - 50	30	90
SPA11	Int – 80 Oth - 60	Ren – 30 Nu – 30 FF - 70	Ren – 90 Nu – 90 FF - 60	20	20	40	Wind – 70 Oth - 40
SPA12	50	70	70	50	60	60	75

Notes – SPAX represents the reference assigned to each interview participant, Ren refers to renewable technologies, Nu to nuclear technologies and FF to fossil fuel technologies, Int to intermittent technologies and Oth to other technologies

With this general observation in mind, it is also important to consider the extent of variation of scoring with respect to each criterion. This can be compared by comparing the standard deviation for each criterion which is presented in Table 19. The standard deviation describes the dispersion of data from the mean i.e. the dispersion of the different scores from the mean, therefore, if the standard deviation of a criterion is high, then the data provided by the interviewees is spread out over a larger range of

values, whereas a low standard deviation suggests that the data provided is spread out over a smaller range and so there is less dispersion of the data from the mean. The standard deviation for these criteria differs as you would expect with value tending to lie between 22 and 28, however, for the final criterion (the contribution to peak load) has a particularly high standard deviation, suggesting a greater range in the values assigned in the scoring of this criterion. In contrast, criterion 6 with a particularly low standard deviation, suggests a much narrower range in the values assigned for the scoring of this criterion.

The mean and standard deviation was also calculated for the scoring of criteria by each participant. A high standard deviation indicates that the participant has a high degree of variation between the scores assigned for criterion and a low standard deviation suggests a much lower degree of variation between the scores assigned for criterion. This data is presented in Table 20 and shows that the standard deviation of participants tends to lie varies from 9.9 (SPA12) to nearly four times that value, 35 (SPA7).

Table 19 – table showing the mean and standard deviation for the scoring of each criterion across participants

Criterion	1	2	3	4	5	6	7
Mean	67.5	59	65.9	45	57.3	41.3	52.3
Standard Deviation	25.4	28.5	24.2	27.1	22.4	19.6	32.5

Table 20 – table showing the mean and standard deviation for the scoring of criteria by each participant

Interviewee	Mean	Standard Deviation
SPA1	78.6	26.7
SPA2	66.9	19.2
SPA3	70.7	12.1
SPA4	37.1	13.8
SPA5	31.4	19.5
SPA6	48.6	24.8
SPA7	42.9	35
SPA8	48.6	25.4
SPA9	42.5	19.4
SPA10	82	29.5
SPA11	26.7	11.5
SPA12	62.1	9.9

The data gained from the appraisal of the data followed by the scoring of each criterion was then used to generate an 'individualised' dendrogram for participants. This process groups technologies based on the performance data and the weighting (score) placed on each criterion (see Chapter 5 for details on the methodology). Two of these dendrograms are analysed below and have been selected to illustrate the divergent perspectives that individuals can have on determining how disparate technologies are from one another. The remaining dendrograms can be found in APPENDIX 1.

Figure 35 – SPA5 – Dendrogram 1 - CCS related technologies highlighted in red text

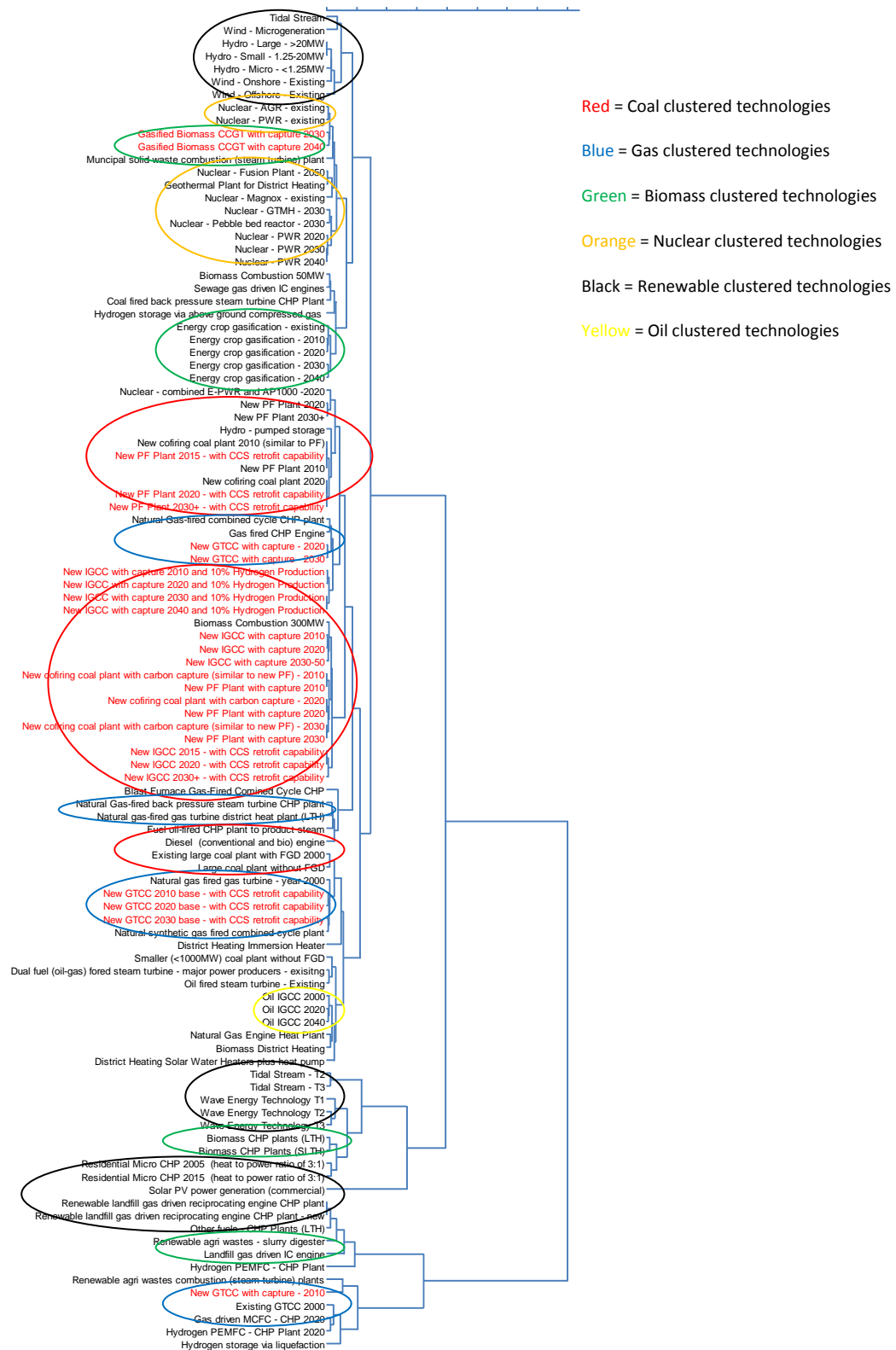
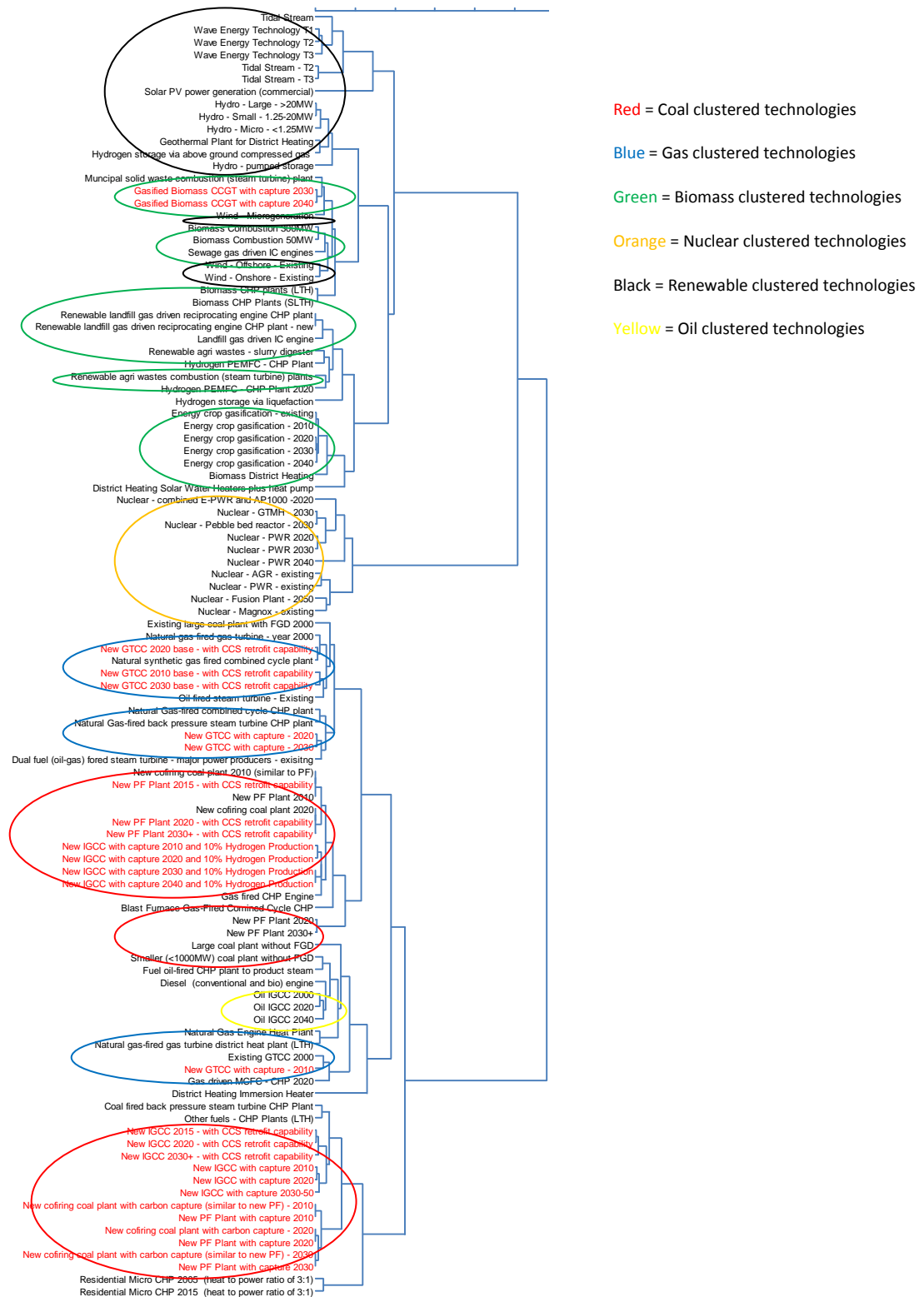


Figure 36 – SPA9– Dendrogram 2 -CCS related technologies highlighted in red text



Generation technologies are often categorized into 3 groups in the academic literature, policy documents and in policy discourse; conventional fossil fuels, nuclear and renewable technologies. However, this categorization is a generalization and does not describe specifically how disparate individual technologies are either within or between these categories. Based on the technology performance data and the scoring of this data by individual stakeholders, this can be explored in more detail in Figure 35 and Figure 36.

7.2.1.1 Dendrogram 1

In contrast to the three groups of generating technologies observed in the literature (fossil fuel, renewables and nuclear), Figure 35 indicates a multitude of clusters of technologies. There are instead, several individual clusters of fossil fuel technologies, located centrally to the dendrogram with CCS technologies featuring within these clusters as opposed to forming separate clusters. Coal makes up the largest of these clusters, is located in the middle of the dendrogram and is centrally bordered at either end by smaller gas and oil clusters. Beyond these fossil fuel clusters there are renewable, biomass-related technologies and nuclear generation technologies.

There are two notable renewable generation technology clusters. One at the top of the dendrogram made up of tidal, wind and hydro generation technologies and one at the other end of the dendrogram containing some tidal stream and wave energy technologies. The separation of these technologies at different ends of the diagram suggests that according to the model performance data and the scores assigned by the stakeholder to each of the criterion that these technologies are more disparate than technologies found in neighbouring clusters such as the coal and gas clusters mentioned. This is also the case for some biomass generation technologies in which some technologies form a cluster at the top of the dendrogram (consisting of energy crop gasification technologies) and another group towards the bottom of the dendrogram (consisting of waste-based technologies such as renewable agri-wastes and landfill gases).

Nuclear generation technologies form two clusters, a larger cluster containing the majority of the nuclear generation technologies and a second smaller cluster made up

of the existing AGR and PWR generation technologies. This second cluster is located towards the top of the dendrogram between renewable and biomass generation technologies.

With a specific focus on CCS based technologies, they appear in 4 clusters (based on their fuel types) with Gasified Biomass CCGT with capture forming its own cluster between the renewable and nuclear clusters at the top of the dendrogram. Clustering of CCS technologies according to fuel type suggests that CCS may not be a single technology 'option' but alternatively, from a diversity perspective, that they are a set of distinct and partly disparate 'options' that all have a common feature (i.e. carbon capture) fitted. This is reinforced by a lack of distinction in clusters between new and retro-fit CCS technologies which are integrated accordingly except for IGCC with capture and 10% hydrogen production which are all located together towards one end of a cluster within the central coal cluster.

7.2.1.2 Dendrogram 2

Figure 36 also consists of a multitude of clusters, however, in this case the coal and gas clusters are concentrated towards the bottom half of the dendrogram with renewable and biomass generation technologies towards the top portion of the dendrogram with a nuclear cluster seemingly separating the two halves. There are not however three individual clusters; renewable, nuclear and fossil fuel. Each portion of the dendrogram is made of a number of clusters. In the top portion of the dendrogram there are 5 obvious clusters of biomass generation technologies but these are interspersed with 3 obvious renewable clusters and some additional hydrogen based technologies. This differs from dendrogram 1 in which biomass and renewable generation technology clusters could be found at both ends of the dendrogram.

Dendrogram 2 only has one nuclear cluster, unlike dendrogram one which has 2 nuclear clusters interspersed by a biomass CCS cluster. The bottom portion of the dendrogram consists of 3 obvious and relatively large coal clusters separated by 3 obvious gas clusters and a single oil cluster, however there are other oil-based technologies littered further afield in the dendrogram which is similar to what is seen for oil-based generation technologies in dendrogram 1. With regard to the coal and

gas clusters there is a similar degree of integration of these clusters which is seen in both dendrograms. However, the bottom half of dendrogram 1 and 2 are very different with a predominance of fossil fuel based clusters in dendrogram 2 which tend to be more centrally located in dendrogram 1 with the bottom half of this dendrogram a mix of gas, biomass, coal and renewable clusters.

With a specific focus on CCS technologies in dendrogram 2, they appear in 4 clusters similar to dendrogram 1, however, the positioning of the clusters and the technologies in each cluster varies slightly. In dendrogram 2 there is a biomass cluster at the top of the dendrogram 2 as in dendrogram 1 and in dendrogram 2 CCS technologies are clustered according to fuel type as they are in dendrogram 1. This reinforces the suggestion made in the comments for dendrogram 1 that the clustering of CCS technologies according to fuel types suggest that CCS is not a single technology 'option' but instead is a set of distinct and partly disparate options with a common feature (i.e. carbon capture) fitted.

When this analysis is extended to all of the dendrograms, then the same pattern of CCS clusters can be observed, further reinforcing the comments above. Each of the dendrograms generated show different relationships between technologies resulting in differing clusters which are also positioned differently relative to one another. This demonstrates that different stakeholder perspectives on the importance of different criteria can have quite different effects in determining how disparate technologies are from one another. In the two dendrograms that have been discussed here, if we look more closely at the scoring of the criterion (see Table 21), we can start to explain what is visualised in the dendrograms.

Interviewee SPA5 places the highest importance on capital costs data and variable operation and maintenance costs. Therefore the cluster analysis groups energy options according to the similarities of the data within these two criteria. This is reflected in the dendrogram, so that the nuclear and capital intensive large renewables (i.e. hydro and offshore wind) are clustered towards the top end of the dendrogram with the cheaper renewables and biomass generation technologies at the opposite end of the dendrogram. In the middle of the dendrograms you find coal which lies

between the two ends cost wise and above coal the more expensive gas generation technologies in a cluster and below the coal cluster another gas generation cluster but this time made up of the cheaper gas generation technologies. CCS technologies are integrated into these clusters according to their relative costs. However, there's a renewable cluster towards the bottom of the dendrogram which contains the most expensive renewable technologies in the model (i.e. tidal stream and wave technology). This is because of the less disparate nature of the data with regard to the other criterion included in the analysis such as plant lifetimes, availability factors and electrical efficiency which are more disparate than the same criterion for the clusters seen higher up in location in the dendrogram.

It is important to point out that all the criteria are considered in the cluster analysis but for the purposes of explaining how the clusters are generated in the dendrograms and the relationships that we have seen, only the most highly scored criterion have been discussed due to the complexity of the process of pairing technologies using this number of criterion.

In contrast interviewee SPA9 places greater importance on capital costs as well as plant lifetime and the electrical efficiency of fossil fuel technologies specifically. With increasing importance placed on additional parameters then the cluster analysis will group technologies most strongly associated according to these three parameters in this instance. This is reflected in the results we see in the dendrogram in which nuclear and big renewable technologies such as Tidal and Hydro technologies which have high capital costs and longer plant lifetimes (i.e. Nuclear ~60 years, Hydro ~40-60 years) are clustered towards one end of the dendrogram and the cheaper gas generation technologies and oil based technologies with lower plant lifetimes (i.e. Oil ~20-25 years, gas ~30-35 years) at the opposite end of the dendrogram with coal generation technologies (plant lifetime ~30 years) centred towards the middle of the dendrogram.

Table 21 – Stakeholder scoring of criteria for dendrogram 1 and dendrogram 2

Interviewee	Availability Factor	Electrical Efficiency	Capital Costs	Fixed O&M Costs	Variable O&M Costs	Plant Lifetime	Cont. to peak load
SPA5	20	20	60	20	60	20	20
SPA9	40	Ren – 0 Nu – 25 FF – 60	65	40	40	60	10

7.2.1.3 Varying data within criteria

The preceding section explored the effects of different weightings placed on criteria by different stakeholders. In addition to this it is also important to reflect on the influence the performance data from MARKAL may have on the structure of the dendrograms. For example, if plant lifetimes were altered what difference does this make to the dendrograms generated? For the purposes of this discussion, two further dendrograms have been generated which are presented in Figure 37, one in which the plant lifetime of nuclear technologies has been increased by 20 years and one in which the plant lifetime of nuclear technologies has been reduced by 20 years (see Table 22 for a summary of the data). A reference dendrogram is also shown for comparison in which the plant lifetime for nuclear technologies remains as it appears in MARKAL.

Table 22 – Summary of nuclear generation technologies and their plant lifetimes

Nuclear Technology	Actual Plant Lifetime (years)	Plant Lifetime +20 years	Plant Lifetime – 20years
E-PWR and AP1000 -2020	50	70	30
AGR - existing	35	55	15
Fusion Plant - 2050	50	70	30
GTMH - 2030	50	70	30
Magnox - existing	45	65	25
Pebble bed reactor - 2030	50	70	30
PWR - existing	40	60	40
PWR 2020	60	80	40
PWR 2030	60	80	40
PWR 2040	60	80	40

Notes – PWR refers to Pressurised Water Reactor, E-PWR refers to European Pressurised Water Reactor, AGR refers to Advanced Gas-cooled Reactors, AP1000 refers to a type of PWR and GTMH refers to Gas Turbine Modular Helium reactors.

The dendrograms show that changes to a single criterion can have a large impact on the estimated disparity of technologies and changes in disparity will have a subsequent

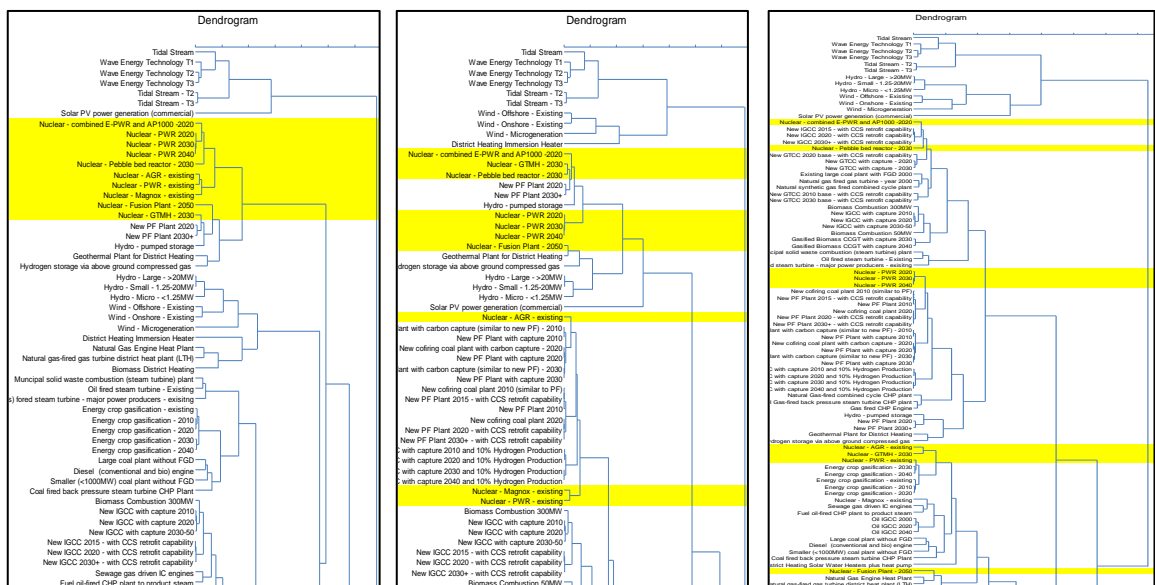
effect on the calculation of the diversity heuristic. This change in disparity arises because changes made to the data have a subsequent effect on the associations between the data in cluster formation which is evident from the dendrograms in Figure 37. The increase in plant life results in a stronger association with other technologies such as Hydro Pumped Storage and New PF Plants which have relatively long plant-lifetimes of 60 years and 40-50 years respectively. This is reflected in the interspersation of these technologies with nuclear technologies which was not evident prior to increasing the plant life of nuclear technologies. When the plant life is reduced by 20 years nuclear technologies become more closely associated with technologies with shorter plant lives such as IGCC and various biomass technologies.

Figure 37 – Snapshot of dendrograms

1. Reference

2. Plant Life +20 years

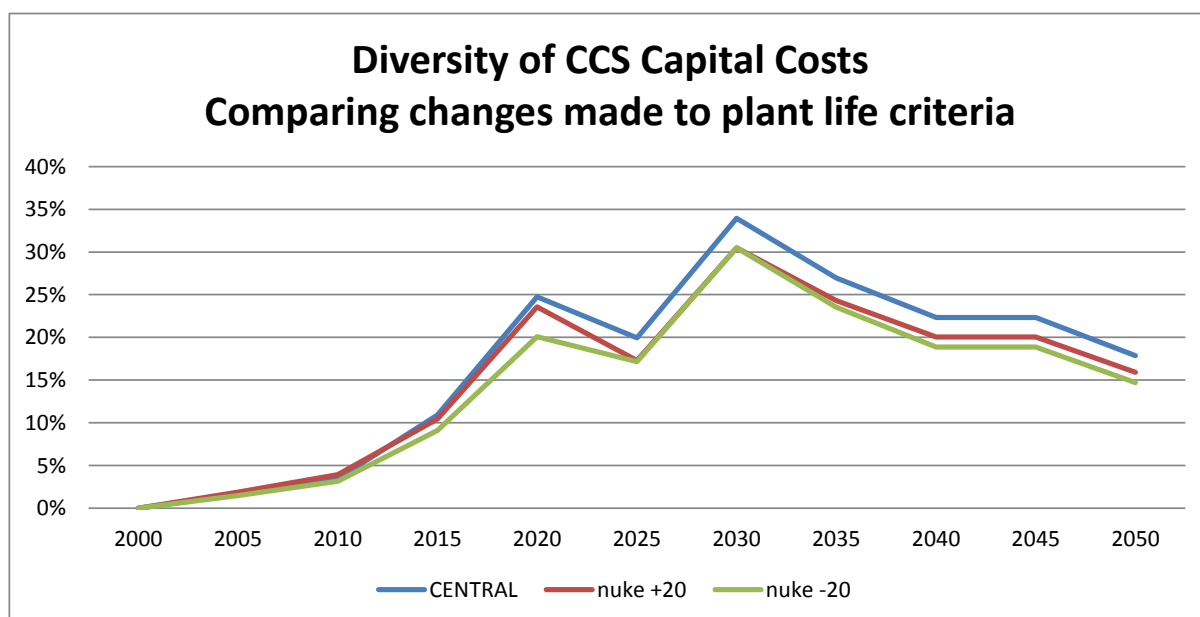
3. Plant Life -20 years



Notes – Illustration of how changing the assumptions for a single technology (in this case plant life for nuclear) can affect on the estimated disparity of technologies. Dendrogram 1 shows the reference case, dendrogram 2 shows the results of extending nuclear plant life by 20 years and dendrogram 3 shows the results of reducing it by 20 years. Nuclear technologies are highlighted in yellow.

Changes to the dataset behind the criteria also have a knock on effect on the overall diversity of a scenario. As you can see in Figure 38, increasing the plant life of nuclear technologies results in a less diverse profile than before changes to the nuclear plant life were made. These changes are in the region of 1-3.5% decrease in diversity and in contrast, reducing the plant life of nuclear technologies is accompanied by a -1 to 4% increase in the diversity of the scenario. Hence small changes made to the data can

have clear effects on the resulting diversity profile generated. However, it is important to note that the overall shape of the diversity profile remains unchanged between profiles with the overall change in diversity between 2000 and 2050, 17% for the central profile, 15% for the profile with an increase in nuclear plant life and 14% for the scenario with a decrease in nuclear plant life.

Figure 38 – Comparing the diversity of a scenario following changes to the dataset

The next section of this chapter will go on to explore the influence that individual stakeholders appraisal of performance data and the relative importance of different criteria can have the diversity profiles of different scenarios. The diversity profile of the reference scenario has been discussed in Chapter 6 and will be discussed in this section alongside the fossil fuel price scenarios which have been selected for discussion in this part of the chapter.

The use of ‘individualised’ disparity matrices from the stakeholder interviews results in diversity profiles which differ significantly from the reference profile (Scenario A) as well as from one another. In particular, the diversity profiles start and finish in different places from one another in 2000 and 2050 respectively. It is important to highlight at this point that in each of these profiles, the only changes made to the calculation of diversity is that of the disparity matrix. The individual technologies (variety) and the proportions of each technology (balance) remains the same throughout.

While many of the ‘individualised’ diversity profiles cluster around the reference profile, there are a number of scenarios that fall above and below this reference profile. This demonstrates that different disparity matrices may lead to more or less diverse profiles. For example, in Figure 39, profile SPA6 has a similar shaped profile as

the reference profile, but is more diverse overall with the diversity peaking in 2035 at 105% versus the baseline compared to the reference scenario where diversity peaks at the same point. The overall increase in diversity is just 40% versus the baseline.

These values are very different which leads to the next question of why is there such a difference. Such differences are attributable to the 'weighting' assigned to individual criteria during the interview stage. In this instance we can see that interviewee SPA7 places the most weight on the availability factor of technology options, with less weight placed on the electrical efficiency and no weight placed on the plant lifetime or the contribution to peak load. These weightings depart significantly from the reference profile which is scored evenly across all criteria. Furthermore, SPA6 has a difference of 80 between the lowest and highest scores. It is this large difference in the weighting between the different criteria that increases the overall estimate of diversity.

In addition to 'individualised' profiles which have a similar shape to the reference profile, albeit more or less diverse, there is also a strikingly different profile, SPA5. SPA5 follows a similar profile to the reference scenario (and the other scenarios) to 2020, where diversity falls sharply and the profile forms a visibly inverse profile compared to the reference profile and looks to be mirroring the profile of SPA6. When the scores assigned are compared significant variations between the two. SPA5 scores capital costs and variable O&M costs the highest, with all other criteria having a relatively low score, whereas SPA6 scores these criteria relatively high in comparison. Although the scores are not complete opposites, the difference in the scores described account for the differences in the profiles.

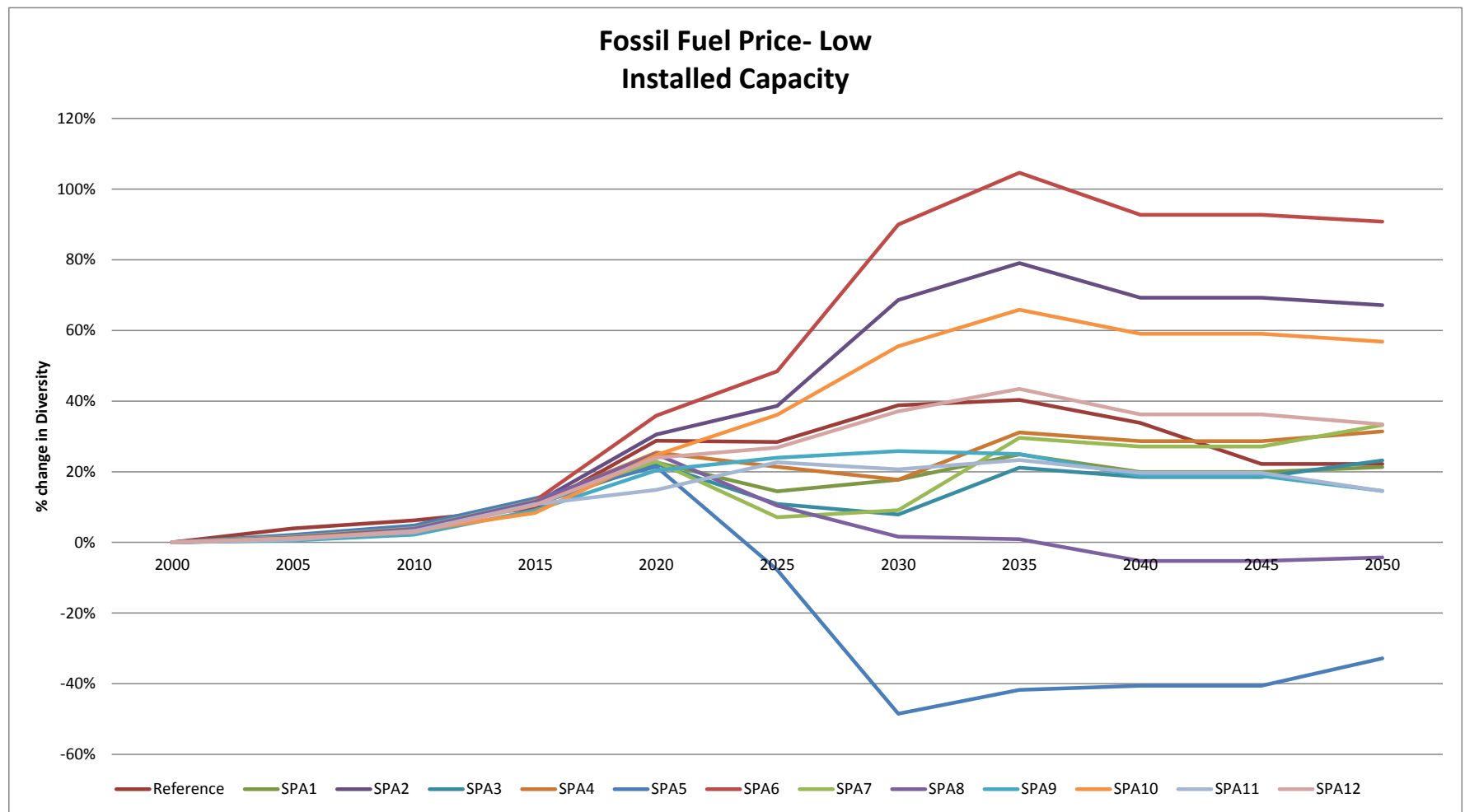
Table 23 – criterion scoring for SPA5 and SPA6

Interviewee	Availability Factor	Electrical Efficiency	Capital Costs	Fixed O&M Costs	Variable O&M Costs	Plant Lifetime	Cont. to peak load
SPA5	20	20	60	20	60	20	20
SPA6	80	60	60	30	40	30	80

Performance under each of the criteria also varies greatly from one technology to another and these variations may be amplified by differences in weightings. For

example, the availability factor varies between 20 and 100%, while capital costs vary from 7.9£/kW to 9854£/kW. Therefore within each of the seven criteria there exists a large amount of variation in the performance data for the technologies which has a knock on effect on the weighting when determining how different technologies are from one another.

Figure 39 – Diversity profiles for the low fossil fuel price scenario generated using ‘individualized’ stakeholder disparity matrices



It is clear that different disparity matrices have an effect on the diversity profile of a scenario and this depends on the weightings assigned by stakeholders to criterion in order to explore ‘how different technologies are from one another’. The next question arising from this analysis is what effect do individual’s disparity matrices have across scenarios?

The ‘individualised’ disparity matrices have a similar effect across all of the fossil fuel price scenario runs. Each leads to a diversity profile which differs somewhat from the reference scenario. More specifically, the reference scenario has a positive gradient until 2035 whereas in three of the interviewee profiles in 2020 the diversity instead falls. These profiles are SPA5, SPA7 and SPA8. This is directly caused by the scorings placed on the criteria by interviewees are the scenarios to which these are applied remain constant and have not been changed in any way. From the scoring assigned (see Table 24) for these three profiles, the criteria ranked similarly are the electrical efficiency, capital costs and variable O&M costs. Electrical efficiency has a relatively low scoring of either 10 or 20 across the three profiles, capital costs scores either 60 or 40 across the profiles and variable O&M costs scores either 60 or 70 across the profiles. The similarity in the scorings for these three criteria specifically, is not present across other profiles, indicating that scoring these criteria in this way is contributing to the decrease in diversity observed for SPA5, 7 and 8. The other criteria from SPA5, 7 and 8 are not similarly ranked across profiles but vary significantly. For example, the availability factor is given a relatively low rank by SPA5 of just 20, whereas SPA7 and SPA8 rank this at 80 and 70 respectively. This is the same for the fixed O&M costs, plant lifetime and contribution to peak load.

It is very difficult to determine, why this combination of scorings across these criteria reduces the overall diversity of the scenario profiles; which occurs consistently across scenarios. It is important at this point to reflect back and remind ourselves that disparity reflects the underlying attributes of a system and that by scoring each of the criterion above, each interviewee is suggesting for each criterion, how important they perceive that criterion to be in determining ‘*how disparate technologies are from one another*’. We know that assigning different scorings to each criterion will subsequently affect their positioning in ‘disparity space’ which can visualised using dendrograms as

explored earlier in the chapter. This ‘positioning’ of technologies in disparity space in turn has a knock-on effect when calculating the diversity of a scenario and subsequently generating a diversity profile. If the variety and balance of each scenario is kept constant as it is, then resulting decreases in the diversity of profiles arises from a decrease in the disparity, more specifically, the criteria of technologies are weighted such that the ‘distance’ between technologies in ‘disparity space’ is reduced. Alternatively, if the variety and balance of each scenario is kept constant as it is, then resulting increases in the diversity of profiles arises from an increase in overall disparity, more specifically, the criteria of technologies are weighted such that the ‘distance between technologies in ‘disparity space’ is increased.

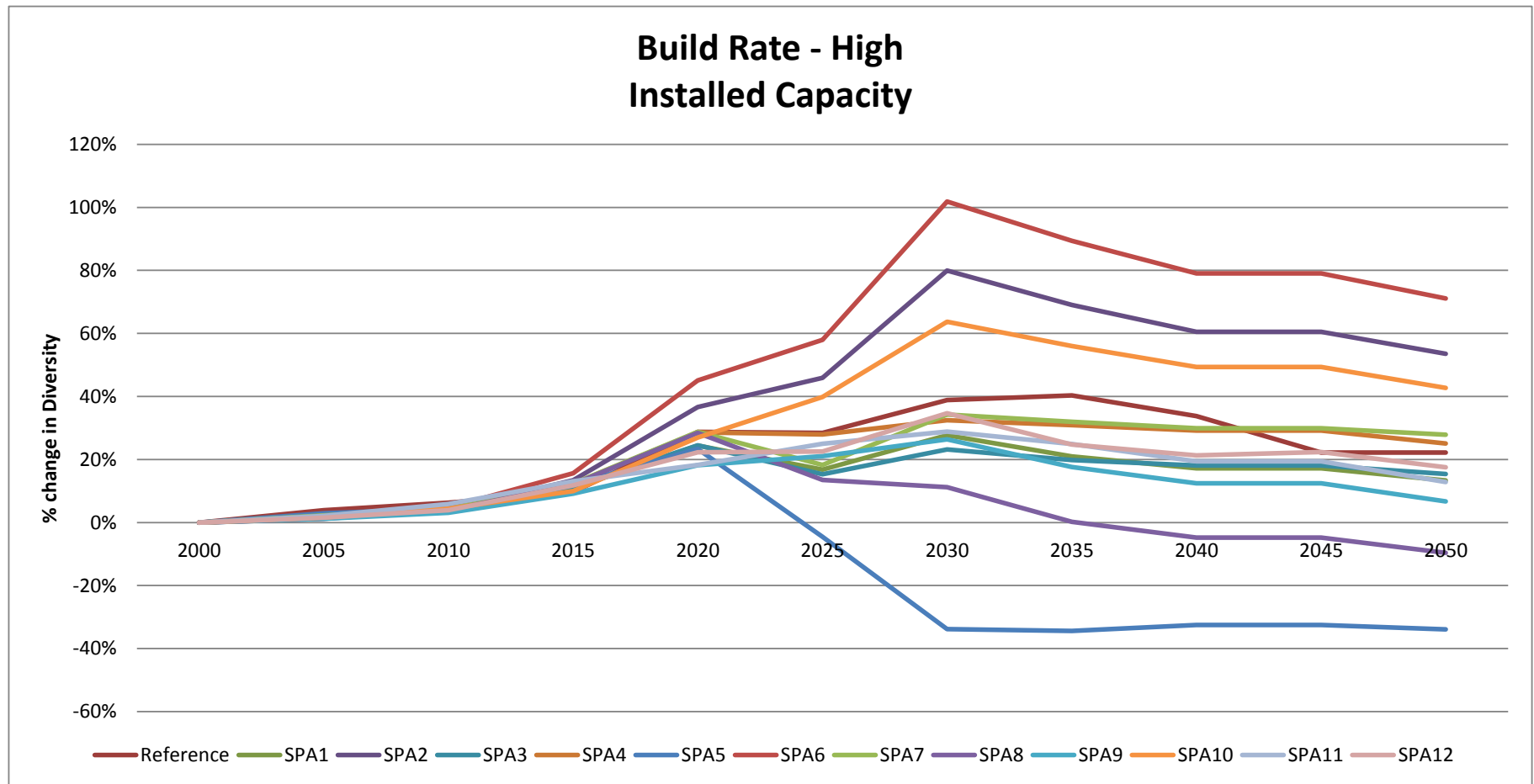
Table 24 – criteria scorings for SPA5, SPA7 and SPA8

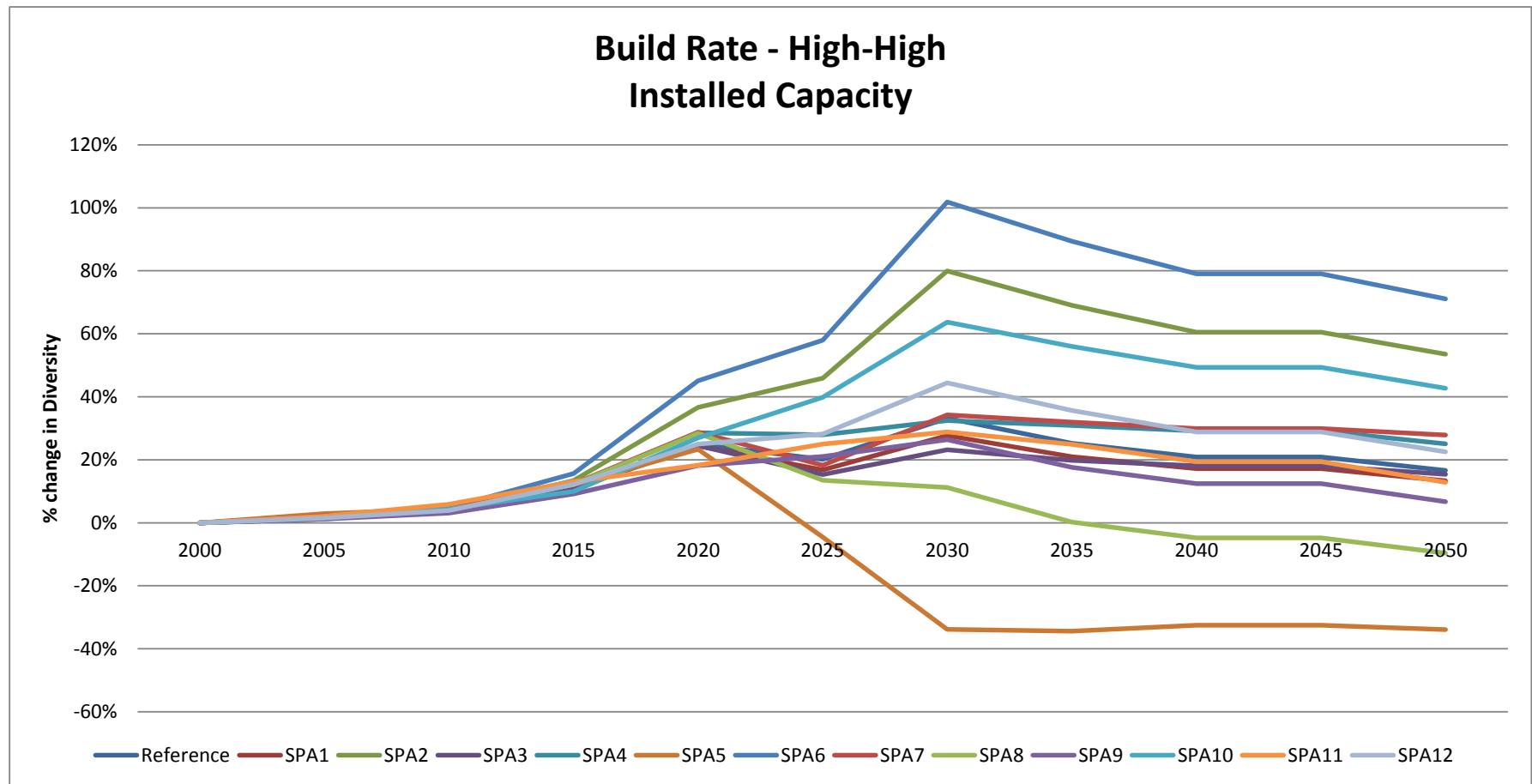
Interviewee	Availability Factor	Electrical Efficiency	Capital Costs	Fixed O&M Costs	Variable O&M Costs	Plant Lifetime	Cont. to peak load
SPA5	20	20	60	20	60	20	20
SPA7	80	20	60	70	70	0	0
SPA8	70	10	40	20	70	60	70

Comparing the diversity profiles for all three fossil fuel prices scenarios in Figure 39 and Figure 40 it can be seen that the ordering of the colours (i.e. stakeholders) is the same for each scenario. For example, SPA6 which always appears towards the top of the graph (high diversity) and SPA5 always appear at the bottom (low diversity). This is because of the weighting placed on the individual criteria. Capital costs has the most disparate data set (ranging from zero to -9854 £/kW) so when more weighting is placed on this criteria, there will be bigger differences in the clusters formed. If the associations from this data are then combined with another highly weighted criterion with a disparate data set - such as fixed costs which vary between 0-3703/kW/year – then clusters are disparate and a more diverse overall profile is observed. This is evident in SPA5 which places the greatest weighting on the two most disparate data sets leading to the most diverse profile. In contrast the opposite is true if a greater weighting is placed on criteria with a less disparate data set such as the contribution to peak load (variation 0-90%) by SPA12.

This helps to demonstrate the importance of disparity in the construction of diversity; different disparity matrices lead to very different diversity profiles for the same scenario. This is in contrast to comparing diversity profiles across scenarios in which each 'individualised' matrix influences the diversity profiles such that each individual's diversity profile for a given scenario appears approximately in the same portion of the graph regardless of scenario. It is important to remember that when comparing across scenarios, that while the disparity matrix is held constant the variety and balance of the scenario changes unlike comparisons within scenarios in which the changeable variable is the disparity.

Figure 40 - Diversity profiles for the high and high-high build rate scenarios generated using 'individualized' stakeholder disparity matrices





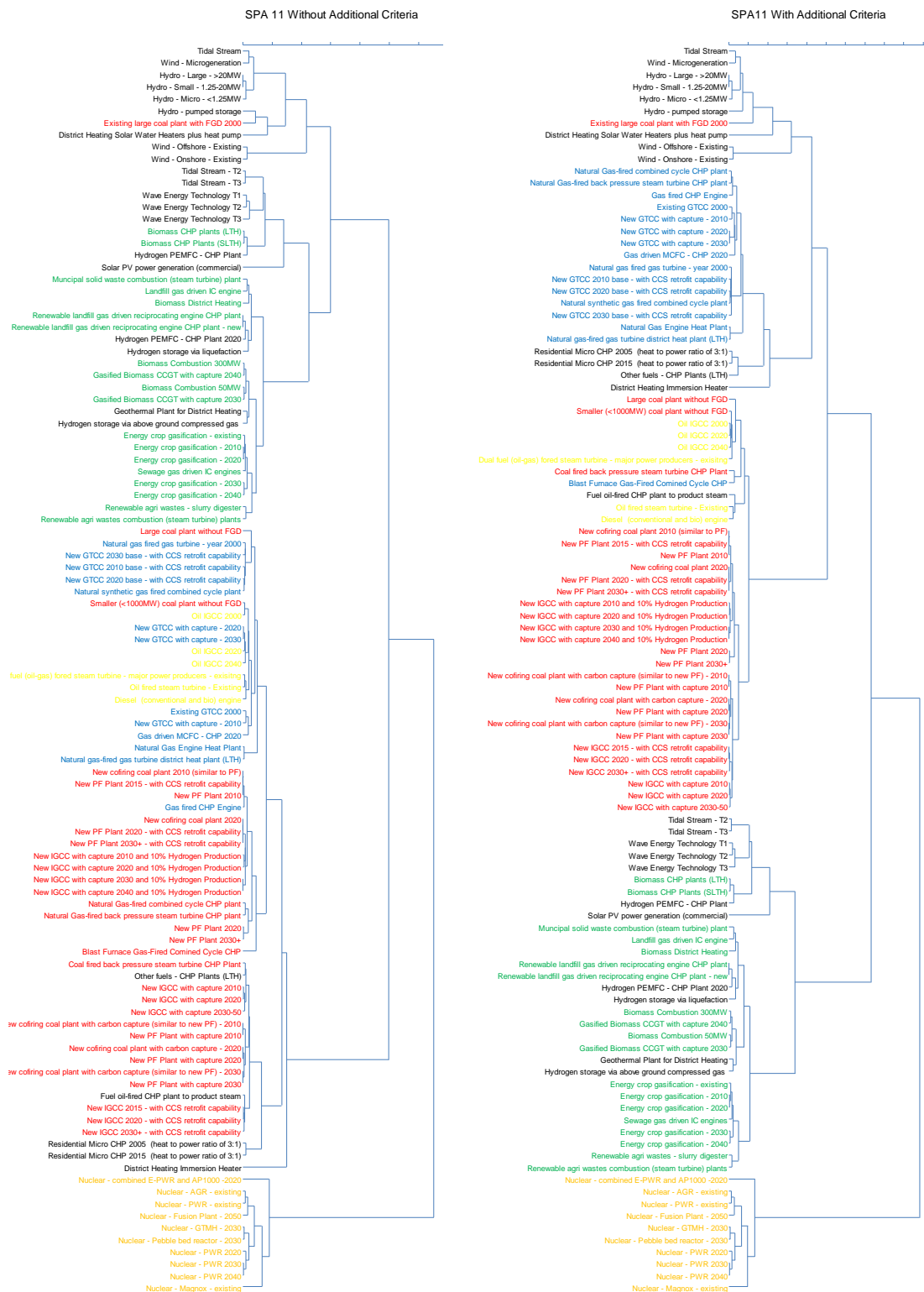
7.3 Additional Criteria

In addition to the criteria discussed previously, each interviewee was asked if they would like to add any further criteria on the basis that they feel that such criteria are important in determining how different technologies are from one another. However, it was not possible to incorporate all of the additional criteria into another set of diversity profiles due to difficulties with collecting the necessary data. As an alternative, interviewee data with additional criteria have been analysed for SPA11 i.e. used to create a disparity matrices and dendrograms (see Figure 41) which has then been used to calculate the diversity profile for selected scenarios for discussion.

Table 25 – Summary of the additional criteria that recommended by each stakeholder

Interviewee	Additional Criteria
SPA1	Security of Supply, Availability of supply, Quantity of supply, Fluctuation of Demand, Time considerations
SPA2	LCOE, Ratio of capital : operating costs, Flexibility factor, Fuel Source
SPA3	None added
SPA4	Technical Maturity/ Project Delivery Risk, Operational Flexibility (Turndown, ramp rates, startup times etc), Revenue Risk (Market, Subsidy), Fuel Availability Risk (esp for biomass / waste projects), Public Acceptability Risk
SPA5	Externalities, Flexibility
SPA6	Despatchable, Low Carbon
SPA7	Schedulability
SPA8	Land area, Import Fuel Supply
SPA9	Geographical Spread – physical location of tech (enable better predictability for techs such as wind), Location of fuels (source and network supply (diversity)) – more diversified network gives a greater resilience
SPA10	Carbon Cost, Public Acceptability, Energy Efficiency
SPA11	Construction Time, Hurdle Rates
SPA12	Fuel type, Renewable, Domestic resources, Land use changes, Carbon Intensity Scale – centralized, decentralized

Figure 41 – Dendrograms for SPA11 (dendrogram 3) with and without additional criteria (dendrogram 4).



Notes - Coal technologies are in red, gas technologies in blue, biomass technology clusters in green, nuclear technologies in orange, renewable technologies in black and oil technologies in yellow.

Interviewee SPA11 added two criteria to their dataset; construction time and hurdle rates. The weightings for each of the criteria are follows:

Table 26 – Additional Criteria for stakeholder SPA11 and the corresponding weightings assigned.

Additional Criterion	Data Added by Stakeholder	Weightings Assigned by Stakeholder
Construction Time	0, 1, 2, 3, 4, 4+ (years)	Nuclear – 80 Coal/Oil – 50 Other - 30
Hurdle Rates	Gas – 8.5% Coal/Oil – 9.5% Renewables – 10% Nuclear – 12%	Nuclear 80 Coal/Oil – 50 Other - 30

Interviewee SPA11 suggested that hurdle rates are subjective and dependent on the market regime. In the model, the technology hurdle rates are 10% for power generation technologies (see chapter 4). At the time of the interview, the Electricity Market Reform consultation was under way in the UK and the interviewee suggested that once this process has been completed then the market structure may differ somewhat to the current regime. The weightings assigned by the interviewee were as follows; nuclear (80), coal/oil (50) and other (30). With reference to the construction time, the interviewee added the data categories 0, 1, 2, 3, 4 and >4 years. The data for this criterion was added by the interviewee based on their own knowledge with the following weightings assigned; nuclear (80), coal/oil (50) and other (30).

The effect of adding these two criteria to the dataset and the corresponding weightings can be seen in dendrogram 3 and dendrogram 4 in Figure 41.

Dendrogram 4 shows interviewee SPA11 data without additional criteria and demonstrates a clustering of fossil fuel technologies centrally to the dendrogram which are made up of small gas and oil clusters (3 or 4 technologies max in each cluster). Below these technologies are a large coal and a large nuclear cluster. Towards the top of the dendrogram renewable technologies are clustered with a large cluster of biomass technologies located between the renewable and the central gas and oil clusters.

More specifically, there are two notable renewable generation technology clusters which both feature at the top of the dendrogram and are made up of tidal, wind and hydro generation technologies, separated by a coal technology. The clustering of renewable technologies towards the top of the dendrogram suggests that, according to the model performance data and the scorings assigned by SPA11 to each criterion, these technologies are closely related and less disparate from one another. This is also the case for the biomass technology clusters, positioned very closely together on the dendrogram, and for nuclear technologies. However, the biomass technologies clusters are located between the renewable and the centrally positioned fossil fuel clusters indicating that biomass technologies are less disparate from these technologies than from nuclear; positioned at the bottom end of the dendrogram.

CCS based technologies appear in 9 different clusters based on their fuel types.

Dendrogram 3 shows interviewee SPA11 data with the additional criteria included. As a result of adding these extra criteria, technologies are clustered in a different way. Renewable technologies still form two clusters towards the top of the dendrogram, but instead of being followed by clusters of biomass technologies, there is a large cluster of coal generation technologies (more than 10 technologies) with the central portion of the dendrogram filled with smaller oil coal and gas clusters. The nuclear cluster appears in the same region, but the biomass technology cluster is now located between this and the central fossil fuel technologies. Therefore, in this dendrogram the biomass technologies are now more disparate from the renewable technologies and less disparate from the nuclear technologies - a very different picture to what was seen in dendrogram 4.

In dendrogram 4 (without the additional criteria), the spread of technologies can be explained by referring back to the weightings placed on each of the criteria (see Table 26). Interviewee SPA11 places least importance on fixed and variable O&M costs (both with a weighting of 20) and plant lifetime (weighting of 40). Instead, they place more emphasis on capital costs, with weightings of 90 for renewables and nuclear technologies and 60 for fossil fuel technologies). Emphasis is then placed on the availability factor of technologies with intermittent technologies weighted at 80 and

other technologies at 60. This leads to large capital intensive generation technologies such as nuclear being clustered at one end and renewable and biomass technologies clustered at the other, with the fossil fuel technologies in between.

However, with the renewable clusters at the top end of the diagram, there are also some large capital intensive renewable technologies included in the cluster, including hydro and offshore wind. This is because these technologies score highly on the capital cost front and also in the electrical efficiency and availability factor criterion, more so in fact than nuclear technologies, hence its distant location. In the middle of the dendrograms you find coal technologies, which lie between the two ends cost wise and above coal, the least expensive gas generation technologies in a cluster and below the coal cluster further gas generation clusters but this time made up of the more expensive gas generation technologies. Thus, taking all criteria together, the more capital intensive generation technologies appear closer to nuclear technologies than to biomass.

The differences between dendrogram 3 and 4 are due to the additional criteria - construction time and hurdle rates (Table 26).

With reference to the construction time, the greatest weighting (80) is placed on nuclear technologies which also takes the longest time to build. Those technologies with shorter construction times such as gas and renewable technologies also have a lower weighting under this criteria (30), making them appear more different to nuclear technologies. Similar comments apply to the hurdle rate criteria where more weighting is placed on nuclear technologies which have high hurdle rates (12%) and less weighting on gas and coal technologies which have lower hurdle rates (8.5% and 9.5% respectively). Therefore nuclear technologies appear closer to renewable and biomass technologies than to coal and gas.

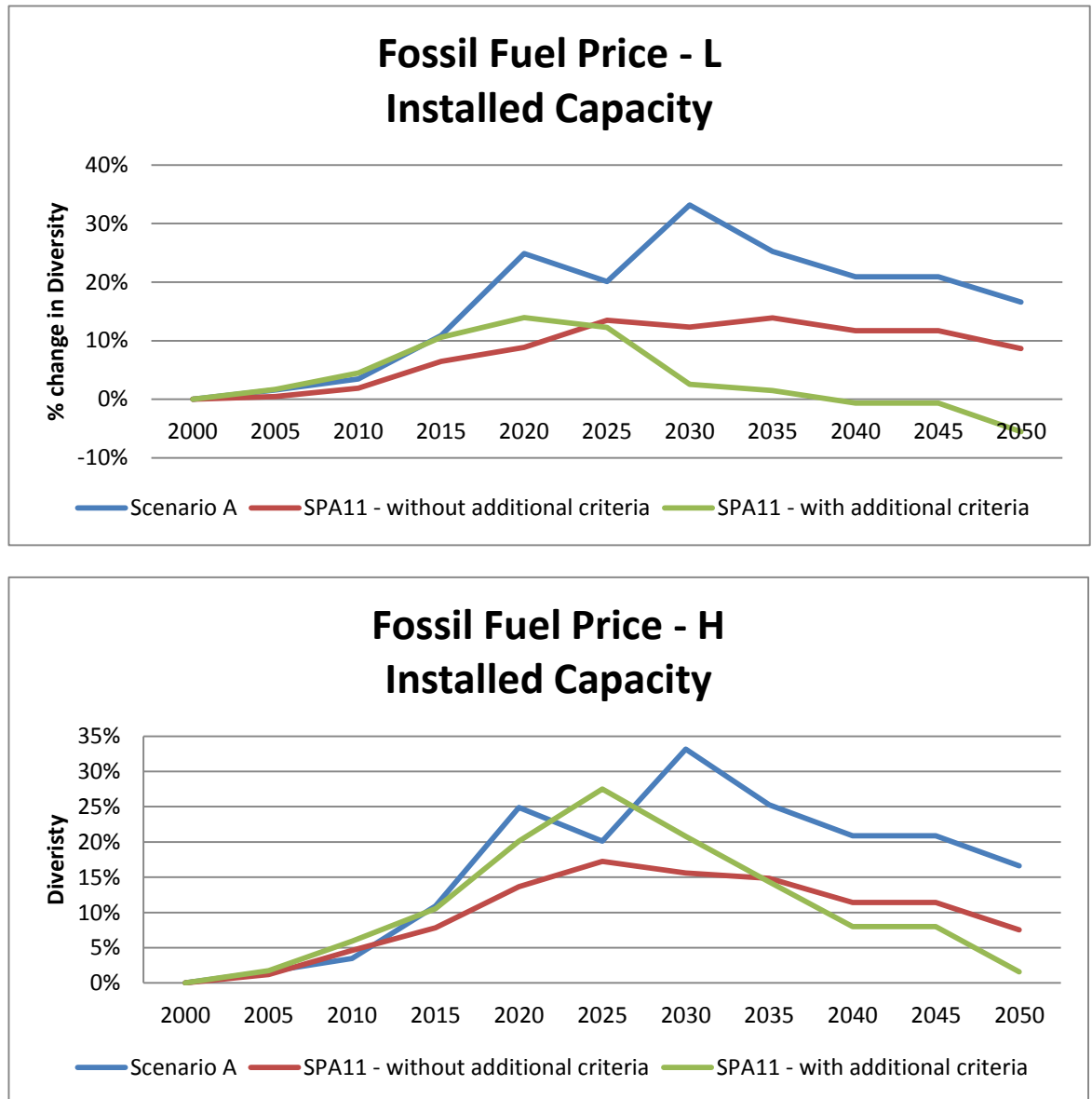
Taking both of the additional criteria into consideration nuclear receives a high weighting for both criteria and also has the highest values within each of the categories and this helps to explain the nuclear cluster appearing at one end of the graph and other technologies, such as some of the cheaper renewables appearing at the opposite end of the dendrogram with fossil fuel technologies lying between the

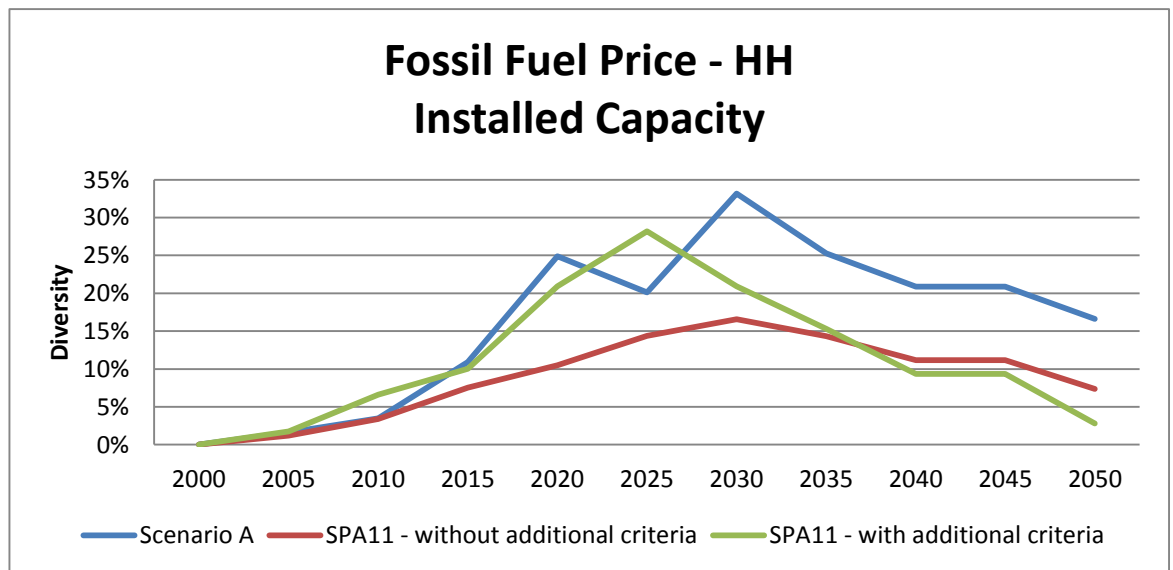
two. In addition, the position of the biomass technologies differs greatly between dendrograms and in dendrogram 3 is positioned next to the biomass cluster. This is interesting because this technology has a low construction time which has a relatively low weighting compared to the nuclear technologies. However, the biomass technologies have a relatively high hurdle rate (second to nuclear at 10%) suggesting less disparity between these technologies, however the weighting of the biomass technologies for hurdle rates is only 30 suggesting greater disparity between nuclear and biomass technologies.

We have discussed how the additional criteria added by interviewee SPA11 affect the disparity matrix generated and its visual representation via the dendrograms. The next and final consideration is the effect that these additional criteria have on the diversity profiles of the fossil fuel price scenarios discussed earlier.

Figure 42 shows the diversity profiles for the fossil fuel prices scenarios using criteria weightings from SPA11, with and without the additional criteria. The profiles for SPA11 for each of the scenarios are closely related, but the profiles *with* the additional criteria indicate slightly lower diversity, with increasing divergence over time. By 2050 there is a 10-12% difference between the two SPA11 profiles. Graphs were also generated for the other scenario sets and show a similar picture. These can be found in APPENDIX 2.

Figure 42 – Diversity profiles with and without additional criteria for interviewee SPA11 for the fossil fuel price scenarios





This graphs show that additional criteria have a direct effect upon the diversity profiles. In the case of SPA11, the effect is a small decrease in overall diversity across all 15 scenarios, indicating that the addition of these criteria reinforces the disparity matrix derived from in the profile without the additional criteria. However, it is not possible to say whether the same result would follow for the other interviewees who typically recommended different criteria. To investigate this further, this process needs to be completed for each of the interviewees and the additional criteria that they suggest. However, the data collection necessary for this is outside the scope of this thesis.

7.4 Chapter Summary

This chapter has provided a detailed analysis of the results of this thesis. More specifically it has presented the results of the diversity profiles generated for each of the MARKAL generated scenarios and related observations back to the original input assumptions and constraints. This chapter then went onto to explore the diversity profiles generated for a selected scenario using the disparity matrices extracted from stakeholder interviews and has demonstrated that disparity does vary according to different stakeholders and that this in turn can affect the values calculated for the diversity profiles using Stirling's heuristic. The final part of this chapter went onto explore the effects of additional criteria in calculating disparity matrices (visualised using dendrograms) and how this, in turn can affect the diversity profile of a selected scenario.

The next chapter in this thesis will provide a detailed discussion of these results in the context of the original research questions set out in chapters 1 and 5.

CHAPTER 8. Discussion

8.1 Chapter Introduction

The purpose of this chapter is to reflect on the empirical data presented in chapters 6 and 7 and to think about how this data can inform our understanding of diversity in the context of the research questions outlined in Chapter 5 and the gaps identified in the literature. In this chapter, this will be tackled by first answering the three sub-research questions identified in Chapter 5. This will then enable further discussion about the overall research question *‘What impact could the deployment of Carbon, Capture and Storage technologies have on the diversity of the future UK electricity system?’*

8.2 Research Question 1

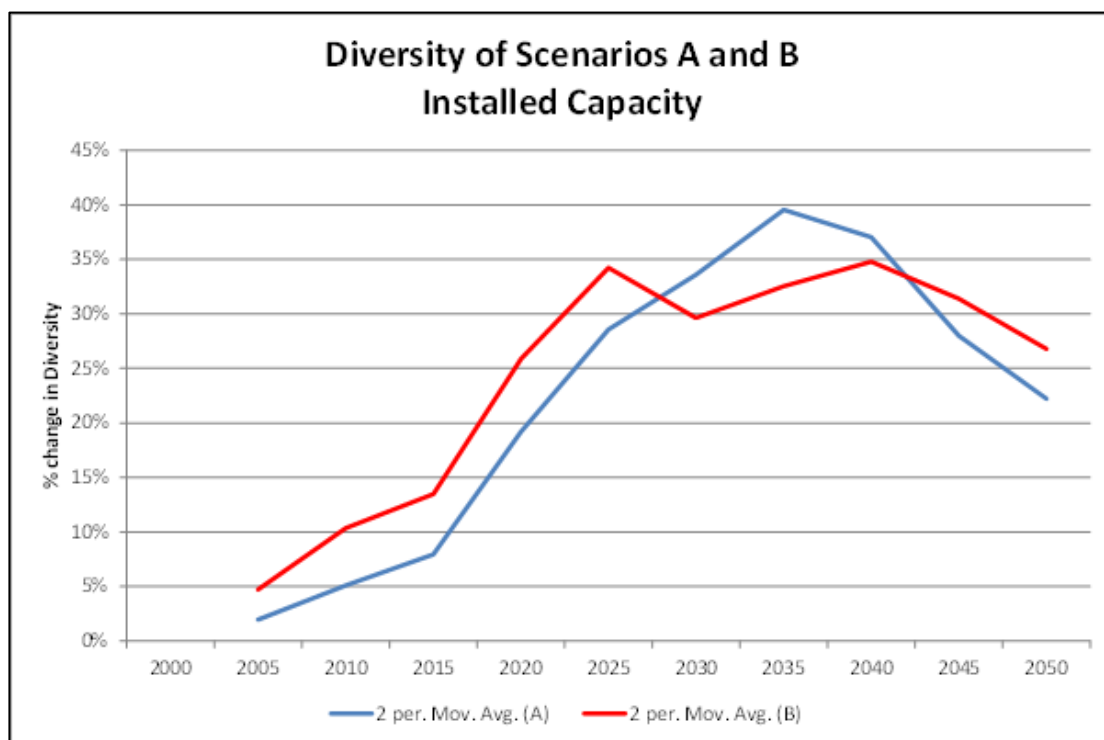
‘What are the potential effects of the deployment of Carbon, Capture and Storage technologies on the diversity of the UK electricity system between now and 2050?’

At the beginning of this thesis we discussed the potential role of CCS technologies in a portfolio of techniques and measures to reduce global emissions and to help avoid the serious consequences of climate change. In the context of the UK electricity system, currently very heavily reliant on fossil fuel technologies, what effects could the deployment of a set of technologies, (although not yet proven at a commercial scale), such as CCS, have on the electricity generating system?

One way to address this question has been to take the current data and assumptions that we have for CCS technologies and look at the effect they have on a model of the UK electricity system such as MARKAL. By varying different model assumptions we can explore the influence that these variables could have on the electricity system and subsequently how they may affect the diversity of the system. This is explored in more detail in the next section; however, before such impacts are explored it is first necessary to look at how deploying CCS may actually affect the diversity of the system itself. A direct comparison was made by generating two scenarios, one in which the model is able to deploy CCS technologies and one in which the model is unable to

deploy CCS technologies (constraints for these scenarios are discussed in more detail in Chapter 5).

Figure 43 - Diversity profiles of installed capacity for Scenario A and Scenario B



Reminder – Scenario A is run with CCS technologies deployed by the model and Scenario B is run without CCS technologies deployed by the model

Figure 43 shows the diversity profiles of Scenarios A and B which were discussed in detail in Chapter 6. This discussion highlighted a difference in the diversity between the two scenarios in the first point plotted on the profile. This was determined to be due to the use of a 2-period moving average to visualise the graphs. It also identified that the diversity of the system in either scenario was the same in 2050, despite the different pathways that the scenarios have taken in diversification. This change in the diversity (applicable to both profiles) of the UK electricity system between 2000 and 2050 is ~22% versus the baseline.

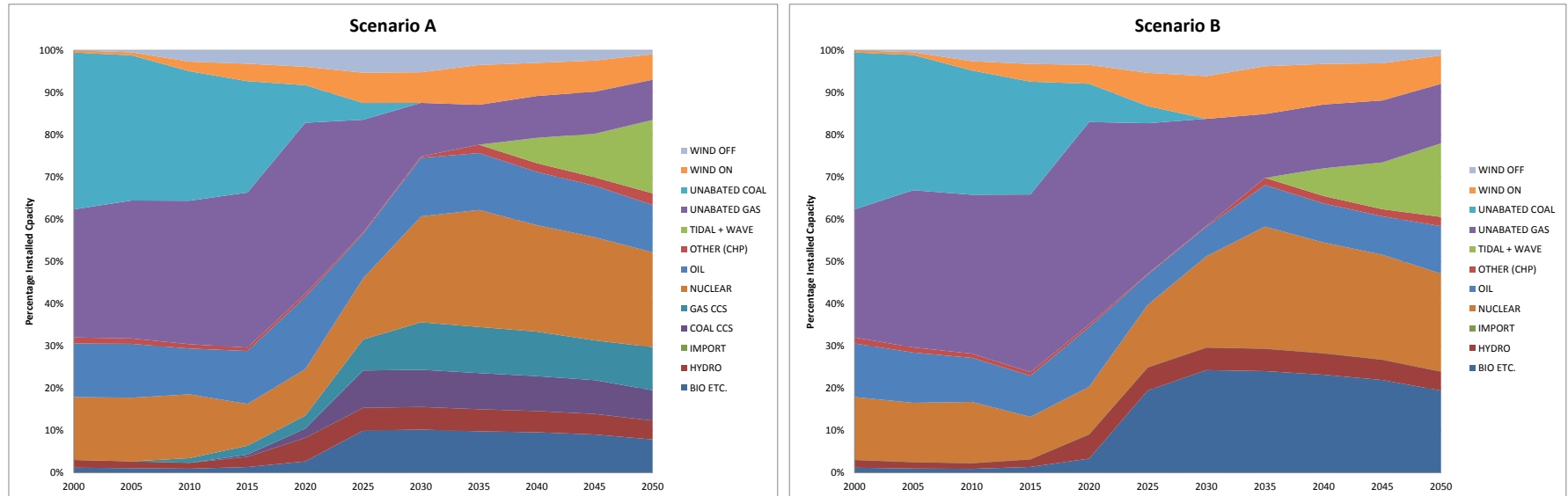
This overall increase in the diversity of the UK electricity systems is driven by two factors. Firstly, the constraints placed on the system, such as an 80% reduction in emissions by 2050 and policy constraints such as the Renewables Obligation and the DECC Carbon Floor Price, which stimulate the deployment of certain low carbon technologies which in turn will increase the diversity of the electricity system.

Secondly, a significant proportion of the UK's gas, coal and nuclear will retire by 2020 and subsequently will need to be replaced by low carbon technologies to meet the emission constraints, again contributing to increases in the diversity of the electricity system.

Up until this point, the discussion of diversity of Scenarios A and B has analysed how diversity changes over time and outlines the reasons for the changes seen in the profiles numerically and the basis for these changes. With this quantitative analysis in mind, it is also important to establish what is actually happening in the system and how this relates to the specific technologies in the model in order to elicit the potential effects of the deployment of CCS on the diversity of the system. One method of visualising this was to take Scenarios A and B and plot the percentage contribution of energy technologies against time for each. This enabled the changes in the contributions made by each of the technology classes to be visualised which will help contribute in explaining the changes seen in the diversity profiles discussed above.

In Scenario A (see Figure 44) up until 2015 the main contributors to the installed capacity of the electricity system are unabated coal and gas with nuclear and oil also making substantial contributions. From 2015 onwards, this portfolio begins to change with unabated coal and gas declining, while onshore wind, retrofitted gas CCS and nuclear all increase in capacity. Contributions from other low carbon technologies such as hydro, biomass, new coal CCS and tidal and wave power begin to emerge from about 2030 onwards. This increase in the *variety* of technologies is reflected in the increase in diversity observed. The more *balanced* contribution of different technologies to total installed capacity also increases the diversity of the scenario.

Figure 44 – Contribution of different technologies to total capacity in Scenario A and Scenario B



In Scenario B, the mix of technologies is similar in the base year to Scenario A with unabated coal and gas being the main contributors to capacity nuclear and oil making significant contributions. As the contributions of unabated gas and coal begin to decline from 2015 there is large growth in biomass technologies, a larger contribution made by unabated gas in Scenario B and the later growth of tidal and wave power as seen in Scenario A. Nuclear remains a strong contributor, although there is little difference in the contribution made between the scenarios. The increased growth in low carbon technologies replaces a large proportion of the fossil fuel stations, particularly unabated coal stations. This results in a differing set of technologies contributing to the installed capacity of the electricity generating system, reflected by an increase in diversity for this scenario.

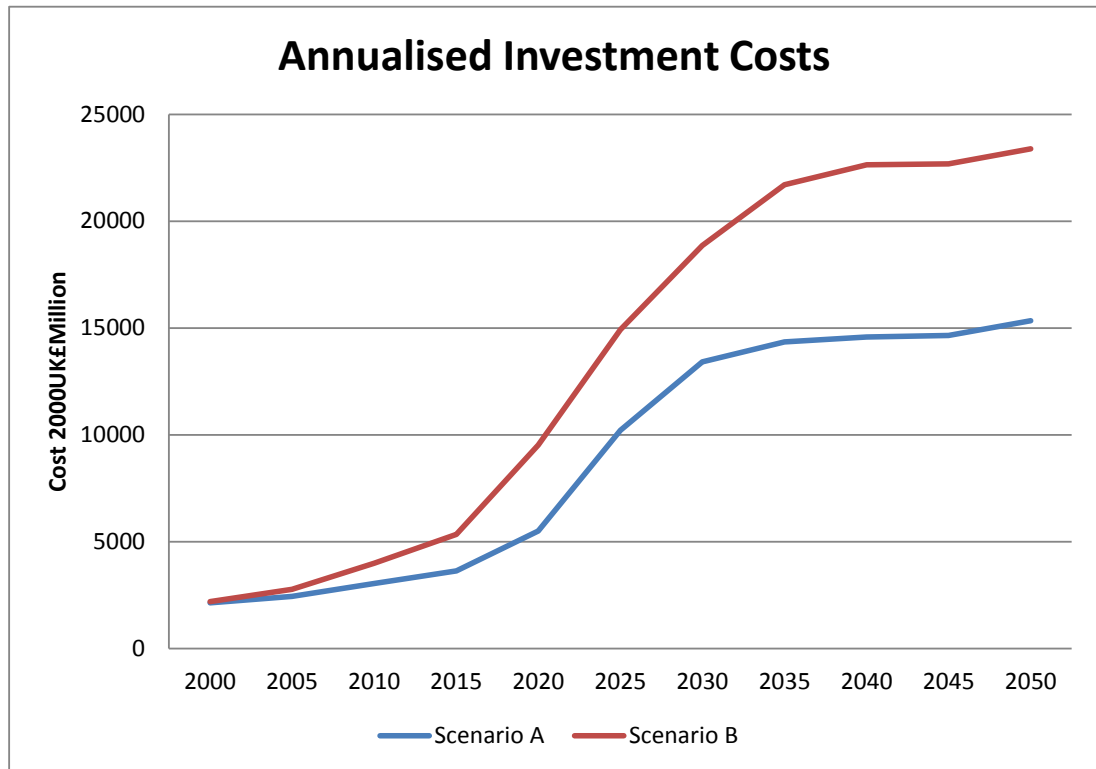
With this in mind, this leads us to consider whether diversity analysis is useful in conjunction with scenario analysis. As discussed earlier, energy models such as MARKAL are useful for exploring future energy pathways and the impact of key variables and assumptions. Given the importance placed upon energy system diversity in policy documents, the addition of diversity analysis to this portfolio of tools enables a more rigorous analysis of the implications for diversity of the deployment of technologies such as CCS. This in turn stimulates further thinking about the meaning of diversity and the wider impacts on the energy system.

However, when considering this metric, it is important to consider the potential trade-offs with other system properties such as cost. We have seen in Scenarios A and B that generating system diversity is the same at the start and end of the scenarios, but the pathway taken by each scenario is different. As a result, the costs of each of the pathways will differ, which may lead to one technology, or set of technologies being chosen over another depending on the differences between the two.

One way of considering such a trade-off is to compare the annualised investment cost of both Scenarios A and B. This is particularly useful in light of the literature discussed earlier in this thesis, which suggests that in the absence of the deployment of CCS technologies, reducing global emissions by 80% based on 1990 levels may cost between 40% and 70% more than if CCS technologies are deployed (see 2.5). The

scenarios developed for this thesis show that if CCS technologies are deployed, then the overall annualised investment cost of technologies are ~35% less than if CCS technologies are not deployed (see Figure 45), reinforcing the observations made in the literature.

Figure 45 – Annualised Investment Costs of Scenario A and Scenario B



So what does this all mean to a policymaker? Quite simply, regardless of whether CCS technologies are deployed or not, there is an overall increase in the diversity of the system between 2000 and 2050 of ~22%. Therefore, CCS is not central to the increase in diversity to the generating system observed, but the advantage of deploying CCS technologies is that they reduce overall annualised technology investment costs, making their deployment particularly favourable as a ‘bridging’ technology to a sustainable economy based on energy conservation and renewable energy sources (Vergragt et al., 2011).

However, it is not quite that simple, because some of the literature also suggests that the deployment of CCS may reinforce technological ‘lock in’ to fossil fuel technologies (Unruh and Carrillo-Hermosilla, 2006, Markusson and Haszeldine, 2008, Vergragt, 2209) making a complete switch to non-fossil fuel technologies more difficult at a later

stage. This switch becomes more difficult because as experience is gained from using CCS technologies then this increases the likelihood that this set of technologies will continue to be used into the future. Therefore switching to non-fossil fuel based competing technologies becomes more and more difficult, as the system has to be realigned to accommodate these technologies (non-fossil fuel) as they are introduced and the existing technologies (fossil fuel) phased out. This, in combination with the fact that CCS technologies are yet to be commercially proven and predictions about the functionality and performance of CCS technologies, particularly those in the earlier stages of development, are not necessarily accurate predictions for the performance of mature technologies. This carries with it a considerable deal of uncertainty, which makes it difficult for policymakers and regulators to make decisions (Markusson and Haszeldine, 2008).

Furthermore, it is not just the uncertainty surrounding technology costs and performance that also require consideration, but also the uncertainty around fossil fuel prices. Fossil fuel prices in the EU are currently at a historical high and as we have seen are set to continue to increase into the future. Continued reliance on fossil fuel technologies such as CCS exposes the electricity generating system to a certain degree of risk as fossil fuel prices increase, particularly if they rise sharply in response to restrictions on supply, as was seen in the oil shocks of the 1970's. The resilience of the system to such shocks will depend on the variety and balance of technologies available to the system and whether in light of such shocks the variety and balance of the system is sufficient to meet demand.

8.3 Research Question 2

'How are key variables and constraints likely to influence the deployment of CCS and what impact could these have on the diversity of the UK electricity system?'

This thesis has explored the effect of three key assumptions on projected CCS deployment and the diversity of the UK electricity system, namely: fossil fuel prices, CCS capital costs, and CCS build rates. Each of these constraints have been varied to produce a range of scenarios and the diversity of each scenario analysed by generating a diversity profile, as discussed in Chapter 5 and presented in Chapter 7. The focus

now, is in summarising the key findings from this exercise and exploring the impact of each. This next section provides an overview of each set of scenarios and the implications of varying each constraint on the deployment of CCS technologies. The summary considers the implications of these findings for the future diversity of the UK electricity system.

8.3.1 CCS Capital Cost Scenarios

Three capital cost scenarios were generated which showed that when CCS capital costs are increased then the capacity of CCS technologies installed is reduced (see Figure 46). Hence, as the cost of CCS technologies increases then CCS becomes a less optimal solution for the model and the capacity of CCS it builds declines. This is also applicable at the individual technology level and accounts for the choice of one technology over another.

Focusing specifically at the individual CCS technologies deployed within each scenario it is useful to look at a break-down of these technologies (see Figure 47). In each of the scenarios, retrofitted gas technologies and new coal technologies form the greatest proportion of the CCS technologies built. This is because this is the most cost optimal solution for the model. More specifically, in the low scenario, retrofitted gas technologies peak in capacity at ~12.6GW and new coal technologies at ~18.5GW. New gas CCS technologies reach less than a 0.5GW capacity in each of the scenarios and retrofitted coal technologies are not built in any of the scenarios. As CCS capital costs increase, the capacity of CCS technologies falls sharply, with the high scenario only reaching a peak installed capacity of ~7.5GW which further falls to ~4.1GW in the high-high scenario.

When discussing the selection of technologies by the model and providing the most cost-optimal solution, it is important to remember that technologies are not selected based on their capital costs alone, but other costs such as fuel costs also play a role. In the scenarios generated, according to the DECC Fuel Price Assumptions, gas prices are lower than coal prices and because fuel costs contribute significantly towards plant costs this helps explain the choice of a gas over coal plant in the model. Further to the cost assumptions discussed, the choice of gas over coal plants may also in part be

owed to the fact that gas plants also have high load factors combined with low annual fixed costs, providing a further advantage over coal. Furthermore, it is also important to note that gas has a lower carbon intensity³⁸ than coal, which refers to the average emission rate of a given pollutant, often expressed as grams per CO₂ per mega joule of energy produced. More specifically, black coal has a carbon intensity of between 843-1171g CO₂-e/kWh whereas natural gas has a carbon intensity between 491-655g CO₂-e/kWh (Bilek, 2008). If gas has a lower carbon intensity than coal, then this is an additional reason that the model will once again favour gas over coal to meet the demand of its carbon constraints.

It is also important to also consider CCS technologies in the context of the whole technology portfolio for the UK electricity system. CCS only accounts for 15-20% of electricity generation and 20-25% of installed capacity in these scenarios. This leads onto the question, how do changes to CCS capital costs affect overall portfolio diversity? The diversity profiles for each scenario were presented in Chapter 6 and these showed very little change in the overall diversity of the installed capacity of the generating system versus Scenario A in 2050. The diversity profiles for the high and high-high capital cost scenarios showed increases in diversity versus the reference scenario prior to converging with the diversity profile of the reference scenario in 2050. Therefore overall diversity in 2050 is similar between scenarios but due to the various assumptions and constraints in the model the profile between the scenarios varies. Furthermore the diversity profile for the low capital cost scenario shows a very different result with a fall in the overall diversity profile of the scenario. This indicates that low CCS capital costs reduce the diversity of the electricity system, possibly because the model favours a single CCS technology.

³⁸ Also referred to as emission intensity

Figure 46 – Installed capacity of CCS technologies for CCS capital cost scenarios

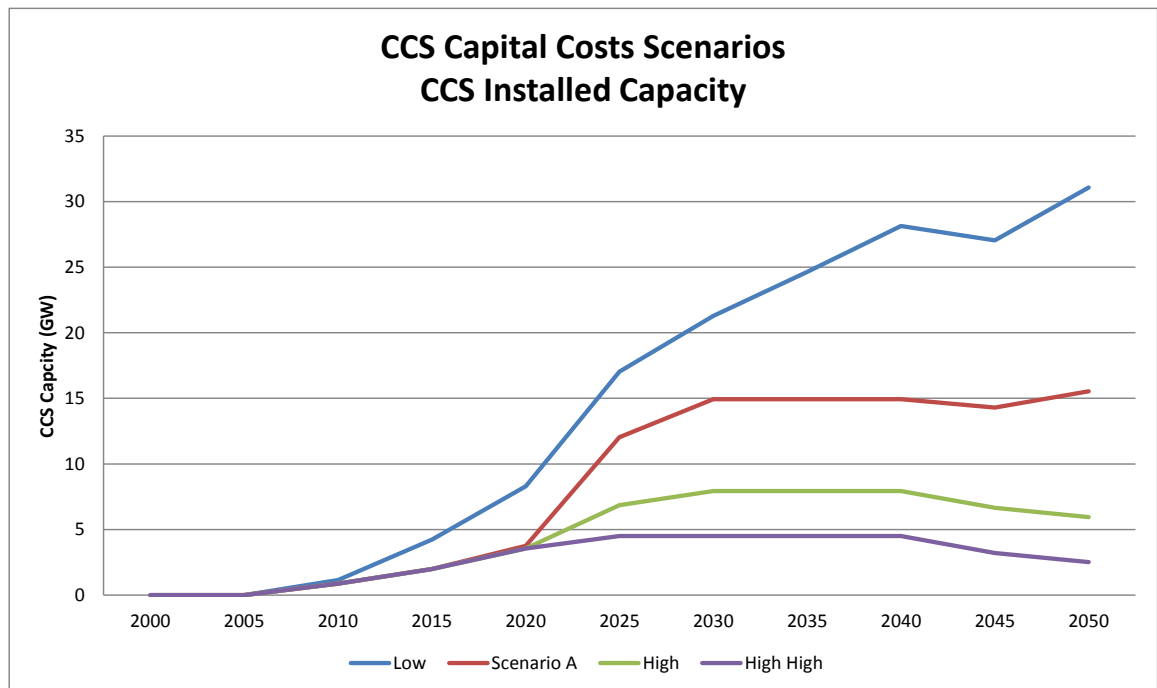
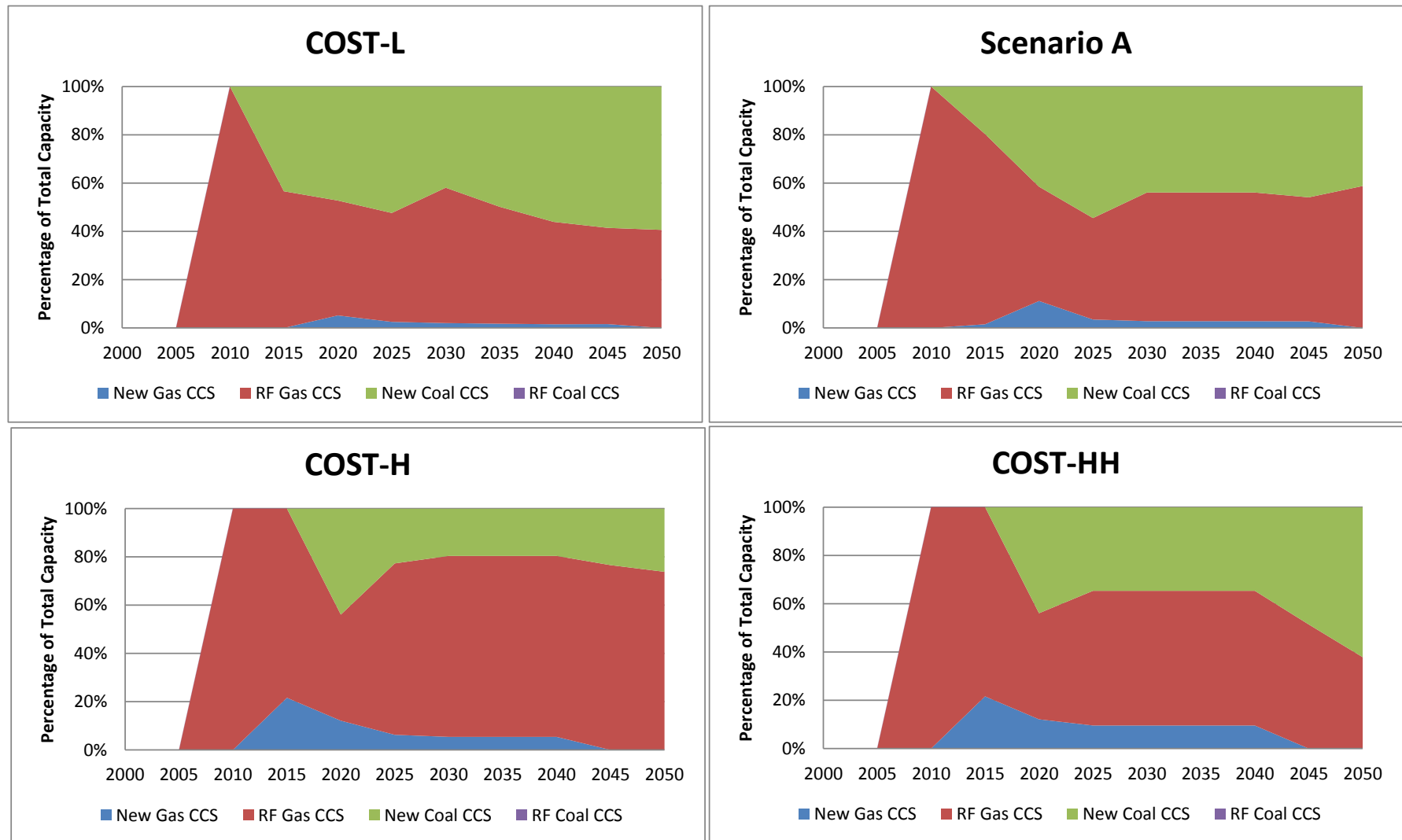


Figure 47 – Breakdown of CCS technology data for the CCS Capital Cost Scenarios, Installed Capacity



Notes - CCS technologies are divided into 4 groups, new coal CCS, new gas CCS, retrofitted coal CCS and retrofitted gas CCS.

8.3.2 CCS Build Rate Scenarios

Three CCS build rate scenarios were generated. They show that when CCS build rates are varied there is an increase in the capacity of CCS technologies installed and the profiles for each of the scenarios follow a similar trajectory to Scenario A (see Figure 48). Focusing specifically on the individual CCS technologies deployed in each of the scenarios (see Figure 49), retrofitted gas is the main CCS technology deployed, reaching a peak capacity of ~10GW, ~19GW and ~23GW in the low, high and high-high scenarios respectively. As discussed for the last set of scenarios, deployment of this technology is based on a number of different costs and again, in this set of scenarios retrofitted gas CCS technologies have the lowest overall costs, making them the most cost-effective technologies to deploy. New coal CCS technologies also contribute to the mix, but account for a much smaller proportion, approx. 13%, 6% and 5% in the low, high and high-high scenario respectively due to higher overall costs. New gas CCS plants also make a very small contribution and retrofitted coal CCS technologies are not deployed at all.

In the context of the whole technology portfolio for the UK electricity generating system, CCS accounts for a maximum of 15%, 27% and 33% of the total generating capacity in the low, high and high-high scenarios respectively. Thus, how do changes to CCS build rates affect overall portfolio diversity? The diversity profiles for each scenario were presented in Chapter 7 which showed that increasing the build rate of CCS technologies resulted in a more diverse generating system in 2050 versus Scenario A. Hence, as the capacity of CCS technologies increases, this causes an overall increase in the diversity of the generating system by up to 16%, at its peak in 2040.

Figure 48 – Installed capacity of CCS technologies for CCS build rate scenarios

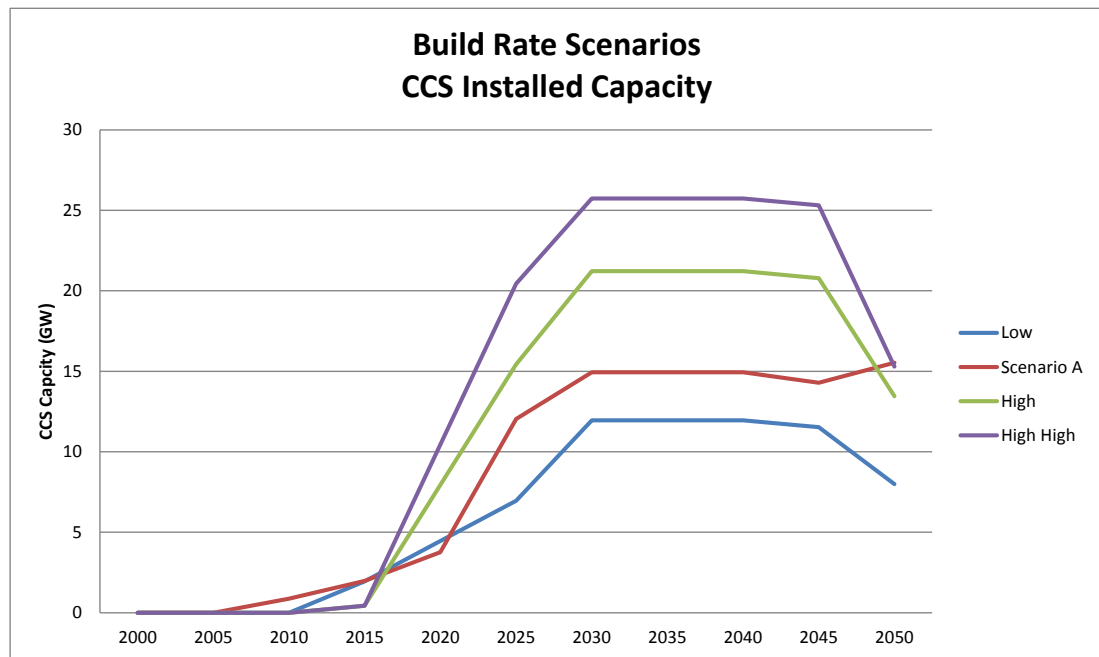
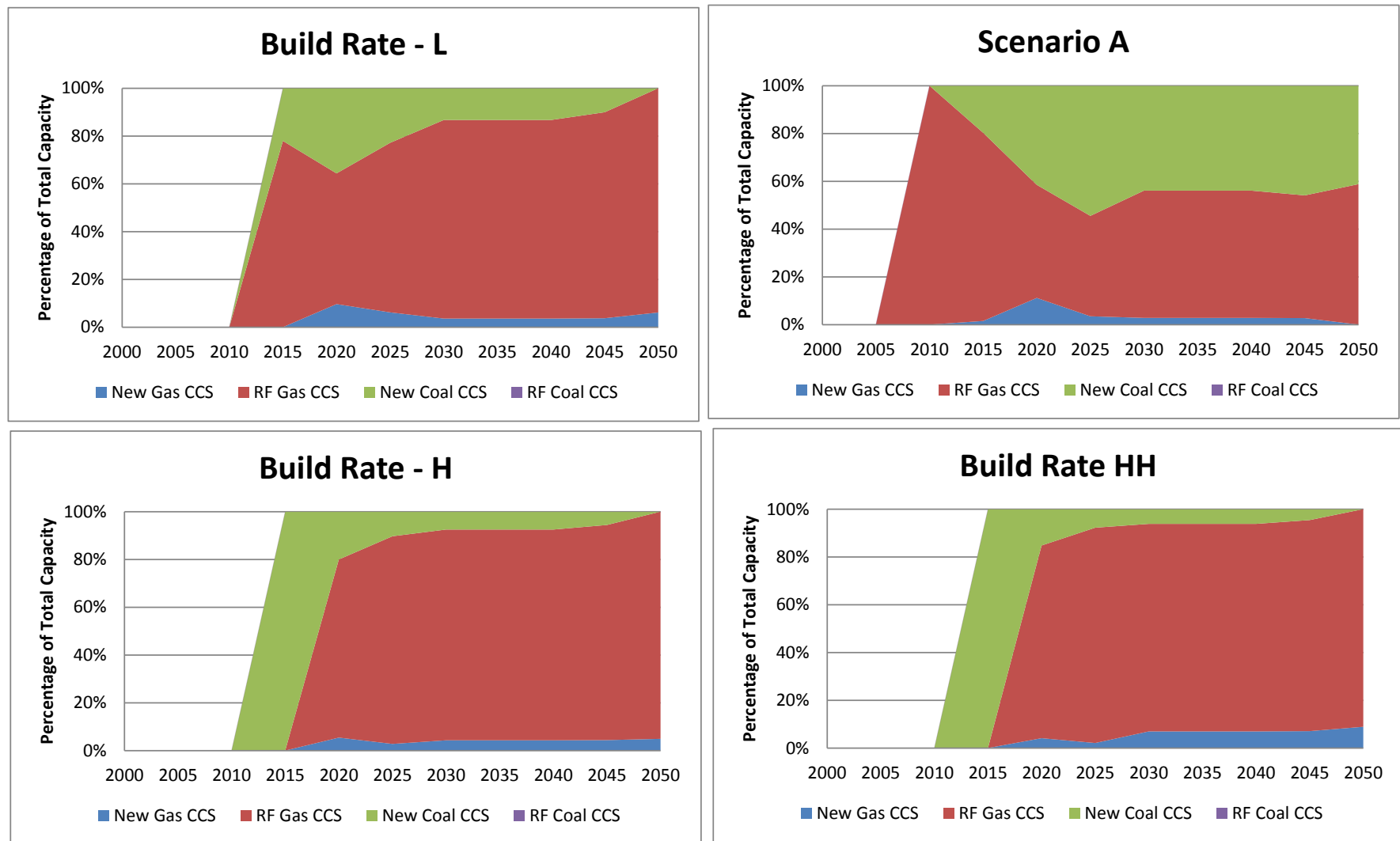


Figure 49 – Breakdown of CCS technology data for the CCS Build Rate Scenarios, Installed Capacity

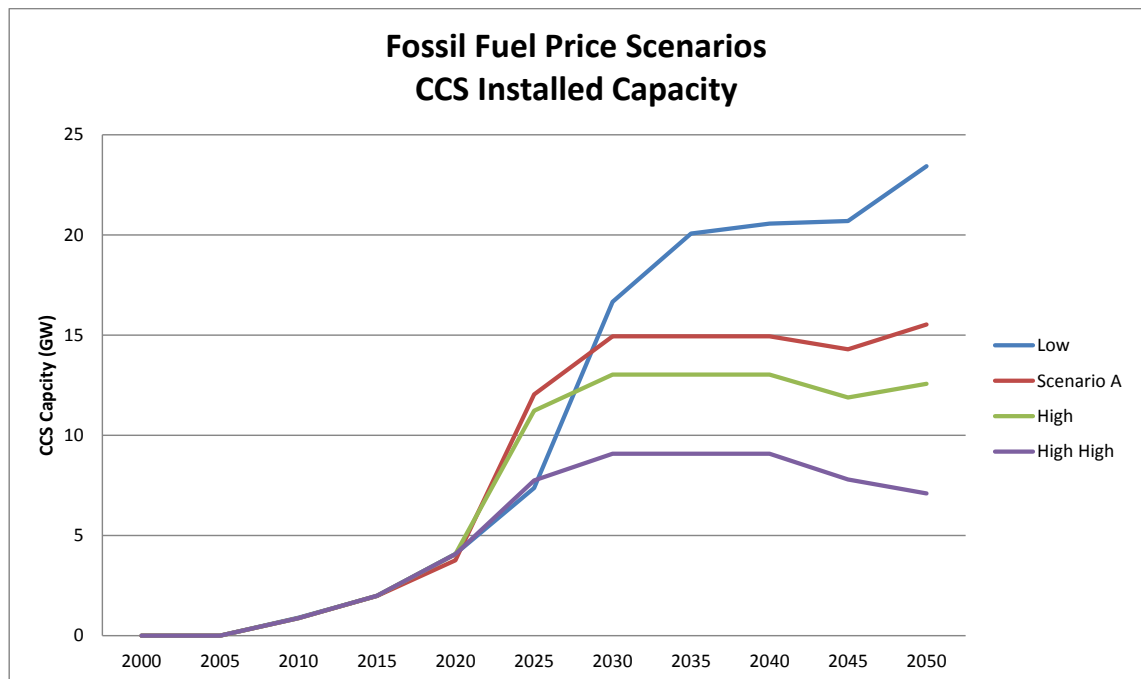


Notes - CCS technologies are divided into 4 groups, new coal CCS, new gas CCS, retrofitted coal CCS and retrofitted gas CCS.

8.3.3 Fossil Fuel Price Scenarios

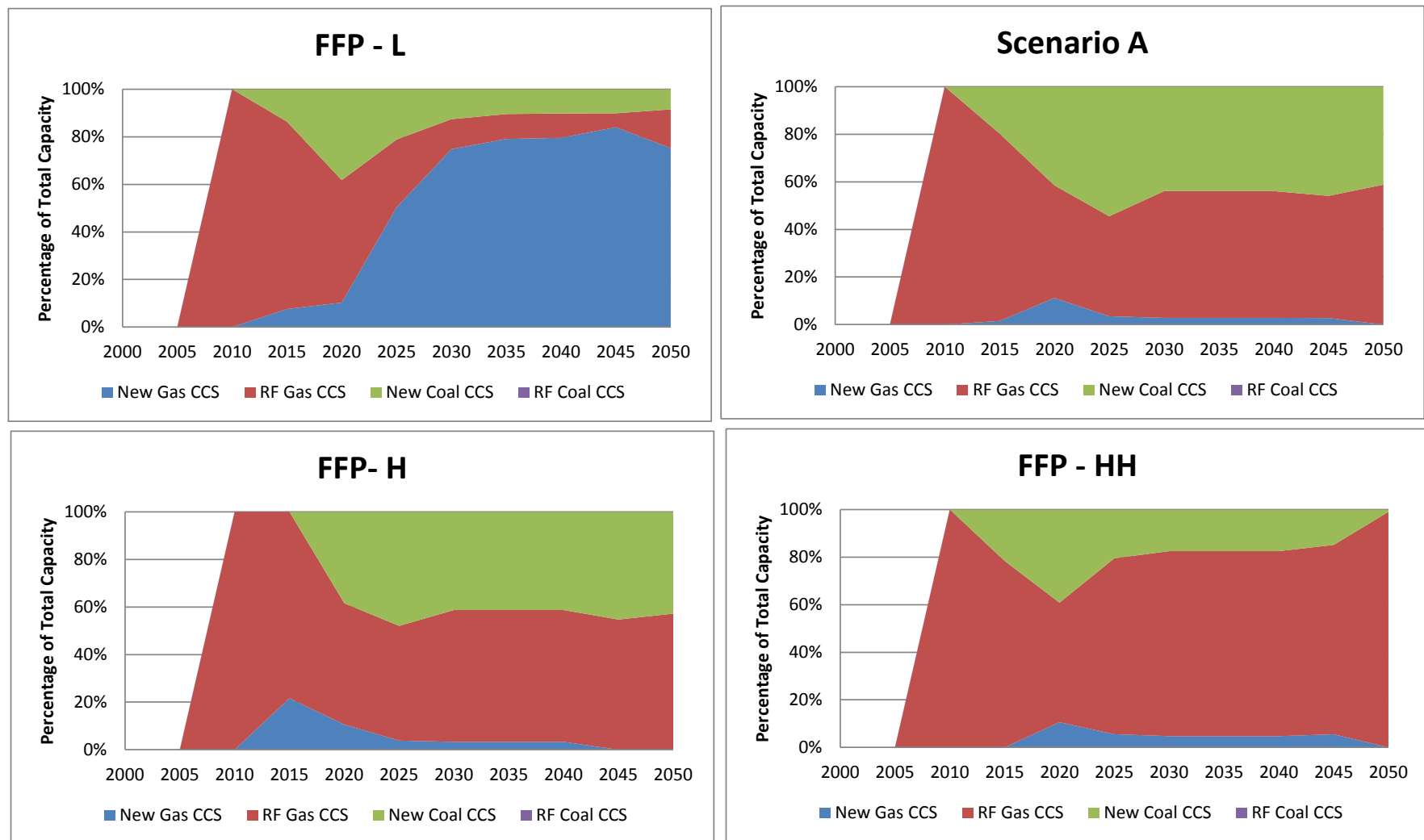
Three fossil fuel price scenarios were generated which show that CCS investment varies inversely with fossil fuel prices (see Figure 50). As fossil fuel prices increase, this stimulates investment in renewables and other low carbon options leading to less investment in CCS.

Figure 50 – Installed capacity of CCS technologies for fossil fuel price scenarios



It is also useful to see which CCS technologies are built (see Figure 51). The overall costs of gas CCS technologies are lower than coal CCS technologies (see Figure 50), making gas largest contributor of CCS technologies overall. In relation to the overall costs, it is interesting to note that coal is cheaper than gas in the fossil fuel price assumptions (see Chapter 5), even though the price of both rises over time. Therefore you might expect to see lots of coal CCS technologies as cheap fuel prices would encourage use of this technology. However, fuel costs are not the only factor to be taken into consideration by the model when choosing technologies as has been discussed previously. It is important to remember that other factors, as discussed previously for other scenarios are also taken into consideration and it is the wider technology costs which drives technology choice, such as capital costs, plant efficiency, technology availability etc.

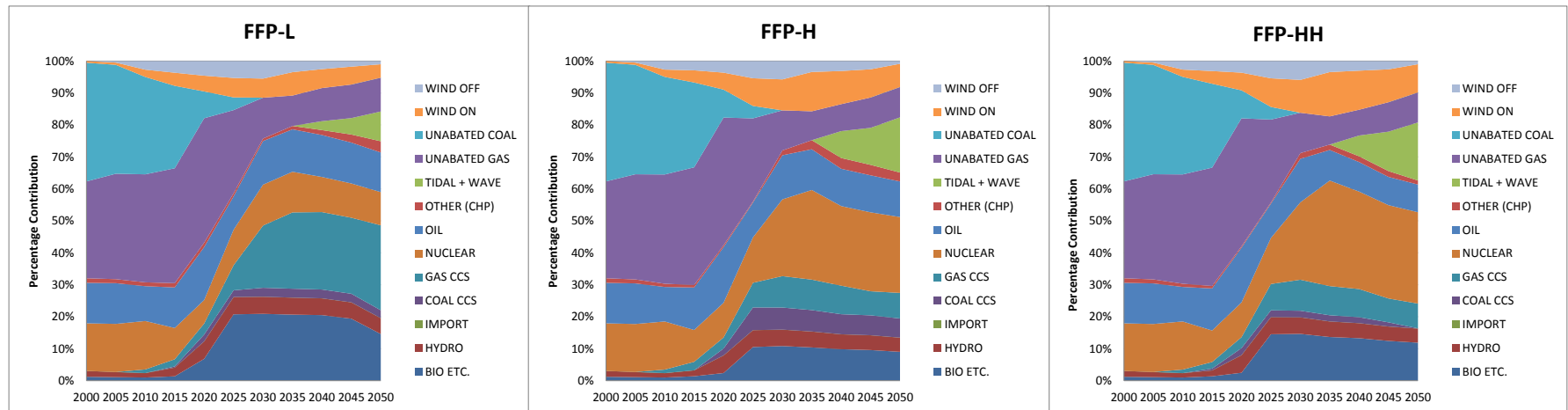
Figure 51 - Breakdown of CCS technologies for the Fossil Fuel Price Scenarios, Installed Capacity



Notes - CCS technologies are divided into 4 groups, new coal CCS, new gas CCS, retrofitted coal CCS and retrofitted gas CCS.

From the perspective of the whole technology portfolio for the UK electricity generating system, for the fossil fuel price scenarios, CCS accounts for a maximum of 11%, 16% and 27% of the total generating capacity in the low, high and high-high scenarios respectively. Thus, how do changes to fossil fuel prices affect overall portfolio diversity? The diversity profiles for each scenario were presented in Chapter 7, which showed that increasing the fossil fuel price is accompanied by a decrease in the capacity of CCS technologies deployed and an overall increase in the diversity of the UK generating system. This diversification can be accounted for by an increase in other, low carbon generating technologies such as nuclear, onshore wind and biomass (see Figure 52), which are driven by various policy constraints in the model, such as the Renewables Obligation; constraining the model to a minimum of 15% contribution to electricity generation from 2020 for included technologies and finally the CPF which rises to £30/tCO₂ in 2020; all of which drive investment in low carbon capacity leading to the changes seen in the diversity profile.

Figure 52 - Contribution of different technologies to total installed capacity in the fossil fuel price scenarios



8.3.4 Summary of Research Question 2

Varying key assumptions changes the model projections of the UK generating system and the estimated diversity of that system. The level of portfolio diversity is dependent on the number of technologies in the portfolio (variety), the proportional contribution of technologies (balance) and how different the technologies in the portfolio are from one another (disparity³⁹). As portfolios of generation technologies increase in variety, then the diversity of the scenario also increases with increased proportional contribution of technologies into the mix. The highest levels of diversity are observed in scenarios with a large number of technologies and a balanced contribution from each. This is applicable to both the installed capacity of the generating system as well as actual electricity generation.

With respect to CCS technologies the model favours retrofit over new CCS plants and gas over coal, due in part to their lower capital costs, but coal CCS frequently dominates electricity generation due to lower carbon abatement costs. This leads to significant amounts of gas CCS technologies either unused or not used to their maximum potential, despite the model assuming perfect foresight. This occurs because the model needs to provide sufficient capacity to meet demand whilst operating within its carbon constraints.

So far, this research question has discussed the effects on the UK electricity generating system of the deployment of CCS technologies, when certain assumptions are applied. However, what does this actually mean for UK energy policy? As discussed earlier in this thesis, there are two main objectives of UK energy policy of relevance, the first is that CCS technologies are part of a portfolio of technologies necessary to achieve climate mitigation targets and the second is that the UK electricity mix should be diverse to help ensure security of supply. These objectives are very much intertwined.

With regard to the first objective, we have seen that CCS is not necessary in all scenarios for the diversification of the UK generating system. In its absence, nuclear plays a significant role with an increasing reliance on nuclear generation and this raises further questions about the role of nuclear technologies in the scenarios and whether

³⁹ Disparity is kept constant across the scenarios relating to research question 1 and 2.

they are actually an artefact of simplified assumptions about the deployment of nuclear technology and issues outside the scope of the model such as public acceptability. However, the most important point to note is that the electricity system still diversifies to a similar extent by 2050, albeit an alternate pathway is taken to achieve this.

From the scenarios generated, it is also clear that higher CCS costs lead to lower deployment of CCS and lower system diversity, while lower CCS costs lead to higher deployment of CCS and higher system diversity. This is because, as CCS-related costs increase, CCS becomes a less cost-optimal technology solution for the model and so alternative technologies are utilised. Alternatively, if CCS-related costs remain relatively low and CCS is the most cost-optimal solution for the model, then electricity system diversity falls, with increasing reliance on CCS technologies.

With regard to the second objective, energy security, the literature suggests that CCS technologies are important in the diversity of the UK electricity system and ensuring a secure electricity supply (see Chapter 2). The idea behind this is quite simple, if the diversity of the electricity system falls, there will be increased reliance on a reduced number of technologies, as a result the security of supply will be reduced. In contrast, if the diversity of the electricity system increases, then the security of supply increases as there is a larger 'pool' of technologies from which to draw upon. However, the results of this study demonstrate that electricity generating system diversity is not reliant on the deployment of CCS technologies. If CCS technologies are not deployed the system still diversifies between 2000 and 2050 to a similar extent and other technologies are instead deployed to meet demand. This weakens the argument that CCS is indeed necessary to ensure security of supply from the perspective of diversity through the variety of technologies in the system. However, the absence of the deployment of CCS technologies comes at a considerable cost as discussed earlier in Chapter 8. Therefore a more valid argument in favour of the deployment of CCS to contribute to ensuring security of supply is more valid from a cost perspective. However, it is important to note that CCS technologies alone will not ensure the security of supply as the vulnerability of the electricity generating system to different risks varies depending on the different technologies deployed within the system as a

whole. For instance, a system largely reliant on CCS technologies is vulnerable to changes to fossil fuel prices, whereas, a system largely reliant on renewable technologies will be less vulnerable to changes in fossil fuel prices and instead, more vulnerable to changing weather patterns. With this in mind, it is important to note that diversity is an important metric for measuring energy security but that it alone is not a sufficient (see section 9.4) and should be considered within a range of indicators that also take into considerations the vulnerabilities and risks that the system may be exposed to as well as considering potential trade-offs between each of these factors and diversity.

8.4 Research Question 3

‘How does the relative emphasis actors place on the various aspects of technology performance affect their appraisal of electricity system diversity in different scenarios?’

In chapter 7 the results of stakeholder interviews were presented and incorporated into disparity matrices to generate revised diversity profiles for each scenario. This data showed the different emphasis (weightings) placed on different criteria by individuals led to significant changes in the estimated diversity of the scenarios. This is because varying disparity matrices changes the value of d_{ij} , which refers to the distance in disparity space separating energy options i and j (see chapter 3 and 5 for more detail), in the calculation of the overall heuristic.

In addition to this, the influence of the performance data itself was considered. This was illustrated by varying the plant life-times of the nuclear generation technologies. This indicated that very small changes in the dataset appraised by the interviewee can have significant effects on the cluster analysis used to generate the dendrogram and on the subsequently generated diversity profiles. This indicates that the disparity matrix generated is very sensitive to small changes in the technology performance dataset, which has a knock on effect on the calculation of diversity in the generation of the diversity profiles. In the example used in Figure 38, this resulted in a couple of percentage point changes in the overall diversity of the profile generated, however, the overall shape of the profile remained unchanged. The high sensitivity of the heuristic to a single change to the dataset, for a single technology set, for single

criteria, may suggest that multiple changes to multiple criteria may have a more profound effect on the diversity profiles generated, highlighting the importance of the accuracy of the data used to generate the diversity profiles. In the case of CCS technologies, where the data used in modelling scenarios is still very uncertain, this needs to be taken into consideration when analysing the resulting scenarios and profiles generated. Furthermore, it is important to remember, that in a similar way to scenario analysis, that the MDA is a useful tool to explore the possibilities for diversity within a system, according to key variables and constraints. It is not there to predict the future diversity of the electricity generating system.

The next consideration is the effect of weighting criteria differently, in addition to the influence that the performance data itself, has on the generation of disparity matrices. It is also important to consider the position of the subsequently generated diversity profiles relative to one another, which remain unchanged across all scenarios. This is ultimately due to the weighting placed on each criterion by the interviewee as discussed earlier; however, it is the variation within the dataset for each criterion that is responsible for the appearance of diversity profiles in the same order across scenarios. Specifically, placing more weight upon criteria that vary significantly from one technology to another, such as capital costs, leads to greater disparity between those technologies and hence to higher estimates of diversity for the relevant scenarios. In contrast, placing more weight upon criteria that vary little from one technology to another, such as fixed O&M costs, leads to less disparity between those technologies and hence to lower estimates of diversity for the relevant scenarios.

Therefore the way in which an individual appraises data and subsequently weights the criteria can have a significant effect on the estimated diversity of different scenarios. For example, individual SPA11 always has the least diverse profile of all interviewees, regardless of scenario assumptions. This is because this interviewee tended to emphasise criteria where the difference between technologies was less pronounced. As a result, the corresponding diversity index was lower. The opposite of this is also true and if criteria are weighted in such a way that technologies appear more disparate then a more diverse profile will be evident. Therefore, regardless of how scenario assumptions change, if an interviewee has a less disparate perspective on how

different technologies are, then the corresponding diversity profiles for scenarios will always be less diverse than if the opposite were true. This is evident when scenarios across all assumptions are compared and the diversity profiles of interviewees occupy the same positions relative to one another in each scenario.

The next step in this thesis was to explore the effects of additional criteria identified by the interviewee as being important in determining '*how different technologies are from one another?*' Data limitations precluded completing this for all interviewees. Instead, this was completed for a single interviewee SPA11, which demonstrated that the addition of criteria reinforces the disparity matrix derived in the previous interview stage, in which the given criteria only were weighted. However, it is not possible to determine whether additional criteria refine the disparity matrix further due to the analysis of a single interviewee only and this work could be extended by completing this analysis for each interview participant.

What do these results mean in the context of UK energy policy? First, they improve our understanding of diversity and illustrate how it can be quantified. Further to this, they provide a framework for the assessment of diversity in combination with scenario analysis provided by energy-economic models such as MARKAL, whilst identifying that there may be trade-offs to consider between the cost and diversity of the electricity system.

Secondly these results illustrate how stakeholders in a specific debate can have significantly divergent perspectives on the same set of technologies contained within a system. When looking at the individual criteria used to assess disparity for research question 3 it becomes clear that those criteria with greater variation within their datasets, such as capital costs (ranging from zero-9854 £/kW) when weighted more heavily have a more profound effect on the diversity of the electricity system. In contrast, when criteria with less variation within their datasets, such as the contribution to peak load (ranging from 0-90%) are weighted more heavily, they exert a lesser effect on the diversity of the electricity system. Hence, the data sets behind each of the criteria are also important in determining the disparity of technologies for a particular stakeholder and the subsequent diversity of scenarios. Further to this,

there is a suggestion within the data that adding criteria and their corresponding data sets to this process may exert further influence on defining disparity for a stakeholder. This needs further investigation.

These findings are particularly poignant in light of the policy making process in understanding the different views of stakeholders and determining the influence that such perspectives may have on technology-based decisions, such as the deployment of CCS technologies. This is particularly notable when the deployment of such technologies may in turn have an effect on other policy relevant factors, such as meeting climate mitigation targets and ensuring the security of supply.

8.5 Summary

This chapter has discussed the empirical results presented in chapters 6 and 7 in the context of the research questions and the potential implications for UK energy policy. This provides a robust basis for the conclusions of this thesis drawn in chapter 9, which will also provide details of policy recommendations as well as summarise the main contributions of this thesis to knowledge.

CHAPTER 9. Conclusions and Policy Recommendations

This thesis has analysed the role of diversity in the context of the UK electricity generating system, with a specific focus on the deployment of CCS technologies to 2050. It has analysed a total of 11 scenarios by varying three sets of input assumptions with each undergoing a diversity analysis as part of the process. The aim of this exercise was to draw out the theoretical and empirical implications of diversity through a process of scenario analysis and subsequently explore the effects of different stakeholder perspectives on diversity. This chapter will present the conclusions to the research questions posed in Chapter 1 and detailed in Chapter 5 and provide policy recommendations based on these conclusions. It will conclude by summarising the contribution of this thesis and avenues of future research opened up by this thesis.

9.1 Answering the research questions

In order to explore *‘what impact could the deployment of Carbon, Capture and Storage technologies have on the diversity of the future UK electricity system?’* three questions were posed. Each is answered below.

1. *What are the potential effects of the deployment of Carbon, Capture and Storage technologies on the diversity of the UK electricity system between now and 2050?*

A comparison of the electricity generating system both with and without the deployment of CCS technologies demonstrates an overall increase in the diversity of the generating system between 2000 and 2050 of ~22 %. This indicates that the electricity generating system will diversify regardless of whether CCS technologies are deployed or not. However, the pathway of diversification differs according to whether or not CCS technologies are deployed. When CCS technologies are deployed then the diversity of the system increases more gradually over time, with a peak in the diversity of the system in 2035. In contrast, in the absence of the deployment of CCS technologies, the system diversifies more quickly with the diversity of the system peaking in 2025 and then again in 2030. Following the peaks in diversity, the diversity

of the system, regardless of the deployment of CCS technologies, then declines and converges in 2040. This decline in the diversity of the electricity generating system is due to decreases in the capacities of onshore and offshore wind, presumably as these technologies come to the end of their lifetimes (just 25 years for wind technologies) and the model meets demand with other growing technologies such as wave and tidal power (also taking into consideration other model assumptions such as policy and emission constraints).

The extent of the diversification of the electricity generating system is technology dependent. This is because the diversity of the system is dependent on the number of technologies deployed in the system (variety), the proportional contribution that each of these technologies makes (balance) and finally, how different the technologies deployed are from one another (disparity). In the comparison made of the electricity generating system, in the presence and absence of the deployment of CCS technologies, the disparity of technologies was kept constant and so the changes in diversity seen can be attributed to the differences between the number of technologies deployed (variety) and the contribution that each of these technologies makes to the system (balance).

2. How are key variables and constraints likely to influence the deployment of CCS and what impact could these have on the diversity of the UK electricity system?

Varying key variables and constraints altered the diversity of the electricity generating system. The changes in diversity observed are dependent on the effect that each of these key variables/constraints have on the number of technologies deployed in the system (variety), the proportional contribution of each of these technologies make to the system (balance) and how the technologies deployed differ from one another (disparity). In the context of this research question, the disparity of these scenarios remains unchanged; hence the diversity of the electricity generating system is affected by changing levels of variety and balance. It is important to remember when making this conclusion that the model used to tackle this research question, is a least-cost optimisation model and so changes in diversity are substantially affected by the cost implications of varying each of the assumptions selected in this thesis.

Three sets of assumptions were varied in addressing this research question; fossil fuel prices, CCS build rates and CCS capital costs and. The results for this thesis show that if you increase fossil fuel prices then this reduces the deployment of CCS technologies, if you increase CCS build rates then this increases the deployment of CCS technologies and if you increase the CCS capital costs then this decreases the deployment of CCS technologies. In all except the build rate scenarios, CCS deployment relates to increasing or decreasing costs associated with CCS, whether it is the cost of the technology itself or the cost of the fuel which subsequently affects technology choice by the model. In the case of build rates, CCS deployment depends indirectly on cost and directly on the build rate assumptions in the model. However, as the assumptions allow increased CCS too be deployed the model chooses this option as it is the most cost-optimal choice to meet demand.

In general, if you increase the capacity of CCS in the electricity generating system then you decrease the overall diversity of the system. This is because in the presence of CCS technologies, other low carbon technologies are deployed to a lesser extent which reduces the variety and balance of generating technologies needed to meet demand in the scenarios and hence reduces the diversity profiles. If, in contrast you decrease the capacity of CCS technologies then you increase the overall diversity of the electricity generating system. This is because in the absence of CCS technologies other low carbon generation technologies are instead deployed to meet demand. This increases the variety and balance of technologies in the generating system and hence increases the overall diversity of the electricity generating system. However, it is important to remind ourselves at this point that in drawing this conclusion; the calculation of diversity relied upon a disparity matrix was constructed without weighting criteria. The consequence of this is that there is no distinction between the relative importance of criteria in determining '*how different technologies are from one another*' and all weighted equally.

3. *How does the relative emphasis actors place on the various aspects of technology performance affect their appraisal of electricity system diversity in different scenarios?*

The results for this thesis show that different emphasis placed by stakeholders on different criteria during the technology performance appraisal subsequently affects the diversity of the electricity generating system. The effect of diversity depends on whether this emphasis leads to a more or less disparate perspective on the differences between the technologies. A more disparate perspective on the technologies generates a more diversity profile for the system and vice versa. With this in mind, it does not matter what variables and constraints are applied to the system, a higher value for disparity (i.e. more diverse perspective on the technologies) leads to a more diverse system in comparison to the reference electricity generating system. Alternatively, a lower value for disparity (i.e. less diverse perspective on the technologies) leads to a less diverse electricity generating system, in comparison to the reference electricity generating system.

In addition to the weightings placed on individual criteria by stakeholders, the dataset behind each of the criteria also exerts an influence in determining disparity and subsequently the diversity of the system. As discussed in chapter 7 and 8 relatively heavy weightings placed on criteria with a large degree of variation in their datasets leads to a more disparate perspective on how different technologies are from one another. In contrast relatively high weightings placed on criteria with less degree of variation in their datasets lead to a less disparate perspective on how different technologies are from one another.

As a result the subsequently generated disparity matrices produced for each stakeholder, when used to assess the diversity of the electricity generating system for different scenarios, results in the generation of profiles that appear when collated in the same position relative to one another. This occurs consistently across all scenarios, regardless of the input assumptions used for scenario generation.

Further to this changes made to the data for the criteria also exerted an effect on the diversity of a scenario by altering the corresponding disparity matrix generated.

9.2 Policy Recommendations

This thesis aimed to explore the impacts that the deployment of CCS technologies might have on the diversity of the UK electricity system to 2050 empirically, by applying a diversity heuristic from the literature. The aim of this was to explore diversity in a policy context and address an idea referred to in a number of government documents but to which the actual meaning and implications of diversity remain unaddressed. This thesis provides four recommendations for policymakers based on the findings in this thesis.

Firstly, an important message for policymakers emerging out of this thesis is the need to recognise that CCS is *not* a single technology but is instead a group of technologies that exhibit disparity between them; evident from comparisons of the performance data for CCS technologies in addition to the different positioning of technologies between dendrograms.

Secondly, CCS is not a group of technologies that is necessary for the generation of a diverse electricity system and subsequently not a strong argument for ensuring security of supply; the model runs carried out for this thesis suggest that electricity generating system will diversify in the absence of the deployment of CCS technologies to the same point by 2050, however as we have seen there are considerable financial implications for this pathway, as demonstrated in Chapter 8. Subsequently, the deployment of CCS is a more valid argument for ensuring security of supply from a cost perspective, than from increasing the variety of technologies in the system.

The third message is that existing government and industry scenarios show a certain degree of optimism in the capacity of CCS that they suggest is built by both 2030 and 2050. For example, the UK Carbon Plan (DECC, 2011a) suggests a capacity of 28GW of CCS is built by 2030 in its core scenario. In comparison, of the 11 scenarios run for this thesis, only one scenario (low CCS capital costs) manages to reach a similar capacity by 2030. Furthermore a report by the CCSA⁴⁰ (2011), is even more optimistic suggesting that 20-30GW of CCS needs to be in place by 2030. In comparison with the scenarios

⁴⁰ CCSA is an organisation which represents members from across industry and includes specialist companies in manufacturing & processing, power generation, engineering & contracting, oil, gas & minerals as well as a wide range of support services to the energy sector such as law, banking, insurance, consultancy and project management.

for this thesis, only 3 scenarios achieve this goal, the high and high-high build rate scenarios and the low CCS capital cost scenario. Each of the scenarios that meet the capacities suggested by the Carbon Plan or the CCSA is unlikely to occur as they involve either very high build rates (*high scenario build rate equates to a maximum build rate of 1.5GW per annum between 2000-2029 and 3GW per annum from 2030-2050, high-high build rate equates to a maximum build rate of 2GW per annum between 2000-2029 and 4GW per annum from 2030-2050*) or very low CCS capital costs. With respect to the build rates, such high build rates are difficult to achieve bearing in mind that during the 'dash for gas' in the 1990's, the only time when annually installed capacity reached a maximum build rate of 2.5GW per annum in comparison with 1960's, 70's and 80's and the rest of the 90's where maximum deployments of installed capacity averaged at ~0.5GW. With respect to the low CCS capital costs, these costs are half of current estimations and the trend for cost estimates for CCS has been too increase then this is an unlikely scenario.

The fourth and final message for policymakers is that when considering the diversity of the electricity system, it is important to take into consideration the influence of stakeholders in the assessment of diversity. This thesis has demonstrated the subjective nature of disparity using Stirling's diversity heuristic which has been extended by exploring the diversity profiles for a set of scenarios concerning the deployment of CCS. It is clear from the results that when considering diversity, the criteria used to assess diversity and more specifically the data sets behind each of the criteria play an important role in determining disparity. Data sets with a large amount of variation such as capital costs which are weighted heavily lead to a more disparate perspective on technologies and in contrast datasets with less variation such as electrical efficiency when weighted in the same way lead to a less disparate perspective on technologies; both of which have a significant influence of the diversity profile for a scenario. By looking at the influence on diversity of different stakeholders perspectives, any discussion surrounding the diversity of the electricity system and how 'diverse' the system should be should take this into consideration.

So, in summary, what does this all mean? Quite simply it suggests that diversity should not just be a term used in UK energy policy literature without detailed thought being

given to both its meaning and implications. As we have seen, diversity is a complex idea, both objective and subjective in nature which must be tackled accordingly in order to generate robust insights about the future of our electricity system.

9.3 The contribution of this thesis

This thesis makes three distinct contributions to knowledge:

Firstly, to the CCS literature; the vast majority of the academic literature to date concerning CCS technologies is technically focused due to the early stage of development and commercialisation of this technology. There is a growing body of social science research concerning CCS technologies centring on modelling work which focuses on generating scenarios concerning climate mitigation and exploring the potential role for CCS technologies within this. Aside from modelling, there is also a growing interest in the areas of the public perception and acceptance of CCS, the economics of CCS, policy frameworks for CCS as well as many other emerging research interests. There is however, no published literature to date about CCS and its relationship with diversity, despite the high relevance to UK energy policy of both CCS and diversity and this is where this thesis makes its first contribution. It provides a detailed analysis of the impact that the deployment of CCS technologies may have in the context of the diversity of the UK electricity system looking forward to 2050.

Secondly, to the diversity literature; there are four notable papers published which attempt to assess the diversity of an electricity system. The first one by Grubb (2006) seeks to address the diversity of the UK electricity system over the coming decades and explore its relationship with low carbon objectives. The second one by (Chung and Ma, 2013) investigates the contribution of energy sources to the energy system and seeks to determine the impact of energy diversity in reducing the risk of energy supply shortages and cost fluctuations in the context of the Taiwanese energy supply structure. However, both studies use the Shannon-Wiener and Herfindahl-Hasslebach indices which fail to address disparity in the quantification of diversity in each of these papers. This thesis, builds on both of these papers by using an index to quantify diversity which takes disparity into consideration, a property discussed extensively in this thesis that due to its subjective nature is often neglected in the literature. As a

result this thesis provides a more rigorous analysis of diversity which also takes into consideration stakeholder perspectives on the disparity of technologies which as we have seen has a knock on effect on the diversity of the system being studied.

However, despite the advantages of Stirling's Diversity Heuristic over more traditionally applied indices, the heuristic applied in this thesis does carry the disadvantage of being very time consuming with regard to stakeholder interviews and the subsequent comparison. An alternative to this, in order to gain quick insights into the diversity profiles of scenarios could be to use a 'reference disparity matrix' in which criteria are equally weighted (as they were for the reference case in this thesis) for the analysis and reserve the original protocol for more in depth studies. The trade-off here is that you are unable to explore individual stakeholder's perspectives on technologies and the subsequent influence this has on the diversity of the electricity system, particularly in light that such stakeholders may exert a certain amount of influence of the policy generation process.

The other two papers by Yoshizawa (2009) and Skea (2010) apply the diversity heuristic used in this thesis. The paper by Yoshizawa is the first application of Stirling's diversity heuristic and is a pilot study focused on assessing diversity in the national electricity supply mixes in Japan and the UK (at a single point in time) with a specific focus on diversity as a strategically important means to foster enhanced energy security. This thesis adds to this strand of the literature by building on Yoshizawa's pilot study by exploring diversity in the context of the UK electricity system until 2050 using scenario analysis with a particular focus on the impact of Carbon, Capture and Storage technologies. Therefore instead of creating a snapshot of diversity at a single point in time this thesis explores how the diversity of the system changes over time according to the variation of different input assumptions and incorporates the views of stakeholders who are currently contributing towards shaping the future of UK energy policy. However, it is also necessary to highlight at this point that scenarios are not predictions of the future but instead a means of exploring different pathways into the future and it is important that this is considered in the context of the methods and analyses used in this thesis.

The paper by Skea explores ways of valuing diversity by analysing the trade-off between system cost and diversity using two stylised situations (one in which all technologies are equally disparate and one in which technologies are not equally disparate) in a simple energy system with defined technologies and costs. The analysis carried out demonstrates that it is possible to design incentive mechanisms which will make energy systems more diverse. This paper does not however, answer some more basic questions such as, do we want a more diverse system, what are the associated implications of such a system and are there any trade-offs that have to be made creating a more diverse system?

This thesis builds on this paper by taking it one step further and using a model (which has been used to inform UK energy policy) with a greater level of complexity as well as adding a scenario component to the analysis which enables changes in diversity over an extended period of time in a range of different scenarios to be explored and the implications of a more diverse system considered further.

Thirdly to the modelling literature; as we have discussed in earlier chapters of this thesis, MARKAL has been used as a tool to inform UK energy policy and UK energy policy has outlined many times the need for a diverse energy system. However, despite this there has been a failure to consider diversity in the context of MARKAL and the scenarios that various studies have generated. Nor has consideration been given to what a diverse energy system should look like or indeed what the implications of a diverse energy system are. This thesis contributes to this strand of the literature by adding a further component to MARKAL studies by enabling the generation of diversity profiles which allow the diversity of the UK electricity system to be explored over a defined period of time and allow comparison between such profiles. This analysis can be carried out with or without stakeholder perspectives incorporated as we have seen, although of course there are trade-offs associated with each case. However, it is important to note that diversity is not a stand-alone metric and this is one of many considerations when looking at the future of the UK electricity system. One consideration highlighted in this thesis is cost, for instance a system without CCS diversity increasing at a faster rate than a system with CCS and a peak in diversity is reached a number of years earlier. However, this more diverse system has investment

costs four and a half times higher than a system with CCS and so this is a significant consideration.

Another consideration is the model itself, as outlined earlier in this thesis CCS is not yet commercially proven, therefore the costs in models such as MARKAL for CCS technologies are at best estimates (hence why a set of scenarios is included which varies CCS Capital Costs). Therefore as the technology develops and more accurate costing's come to light then the diversity profile of the UK electricity system may change significantly and this also needs to be considered when drawing conclusions from any study incorporating scenarios.

9.4 Avenues for future research

There are several avenues of further research that the work in this thesis opens up. Two of these will be discussed in more detail in this final section of the chapter.

1. *Using MVP theory, a parametric approach, to assess diversity and enable comparison of the results of this methodology with the results of the heuristic used in this thesis.*

In chapter 3 the concept of mean-variance portfolio theory was discussed as an alternative parametric approach to assessing diversity. In this discussion, we explored two critiques of this theory from Stirling (1994b) and Roques (2007). Both critiques focus and disregard MVP theory in determining diversity essentially because of production and fuel price costs. More specifically, the former critique suggested this was the case because fuel price movements, which are fundamental in determining technology generation costs, have no pattern and that 'decisions in the complex and rapidly changing environment of electricity supply are unique, major and irreversible' and that 'ignorance⁴¹ rather than risk⁴² or uncertainty⁴³ dominates real electricity investment decisions'. The latter critique suggests this because in liberalised energy markets such as the UK private investors cannot be expected to compare different

⁴¹ Ignorance exists when there is no basis upon which to assign probabilities to outcomes, nor knowledge about the many of the possible outcomes themselves STIRLING, A. 1994b. Diversity and ignorance in electricity supply investment: addressing the solution rather than the problem. *Energy Policy*, 22 (3)..

⁴² Risk refers to a probability density function which may meaningfully be defined for a range of possible outcomes *ibid.*.

⁴³ Uncertainty exists when there is no basis upon which to assign probabilities *ibid.*

generating technologies on their production costs, but rather on their expected risks and returns. However, such critiques are responded to by academics Awerbuch and Berger, experts on the application of MVP to energy portfolios. These authors suggest in response to both of these critiques that while no random event may be duplicated, in the case of equity and stocks historic variability is widely considered to be a useful indicator of future volatility and suggest that this is no different for fossil fuel prices, O&M outlays and investment period costs. However, the authors do point out that certain fundamental changes in the future such as new technologies or market restructuring could create 'surprises' by altering observed historic risk patterns and that such changes are unpredictable. In response to such changes, Awerbuch and Berger suggest that these possibilities should not drive decision approach and they find it more plausible to assume the totality of random events over the past three decades sufficient to cover the reasonable range of expectations for the future (Awerbuch and Berger, 2003b).

In light of these conflicting ideas in the literature it would be interesting to repeat the assessment of diversity using the scenarios generated for this thesis using MVP methodology to enable a comparison of the results between the two methodologies.

2. Analysis of the relationship between diversity and energy security and exploring possible trade-offs between cost and diversity in helping to ensure a secure energy supply.

This thesis has identified that CCS is not an essential technology in ensuring the future security of the UK electricity supply. In the absence of the deployment of CCS technologies the UK electricity generating system will diversify to a similar extent regardless. However, this thesis has suggested that the deployment of CCS technologies may contribute towards ensuring the price security of the UK electricity supply. Security of supply and more specifically price security are both very important in light of climate mitigation and the emissions targets to which we are legally bound. However, it is beyond the scope of this thesis to explore these relationships in the necessary detail to enable conclusions to be drawn on how diversity directly affects energy security. However, this thesis does provide a solid basis for further research in

this area by expanding on the research presented here and using it to explore diversity and energy security in more detail by incorporating energy security metrics into the analysis of diversity and extracting 'cost' data on a scenario by scenario basis in a similar way to this thesis. Hence as well as generating a series of diversity profiles which can be compared across a set of assumptions, the energy security of such scenarios across a range of assumptions and using a range of indicators could also be generated. This would help to generate a more holistic approach to the investigation of diversity and the wider implications of diversity for security of supply of the electricity generating system.

Thus as changes to the 'security of supply' and the 'diversity' of the electricity system across sets of assumptions are explored, potential trade-offs between cost, diversity and energy security would be exposed and the implications of these opened up for further investigation.

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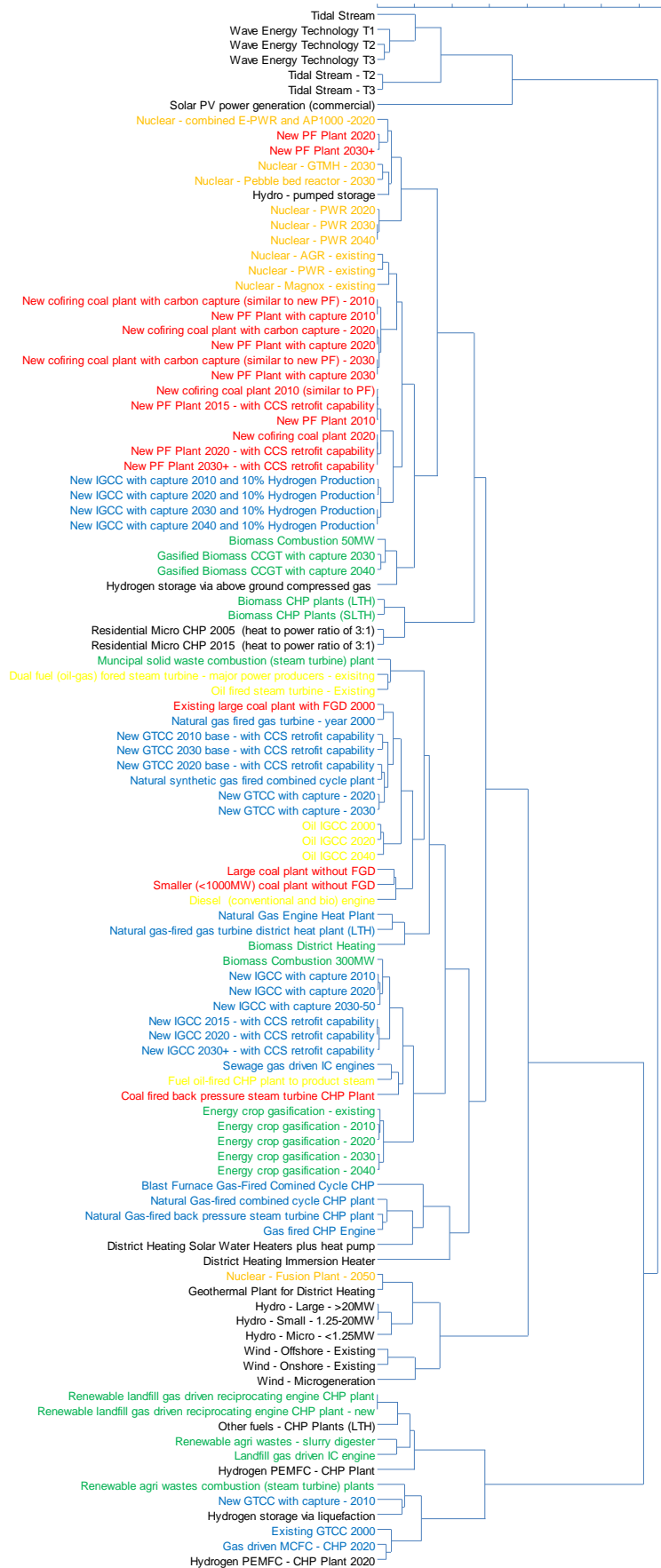
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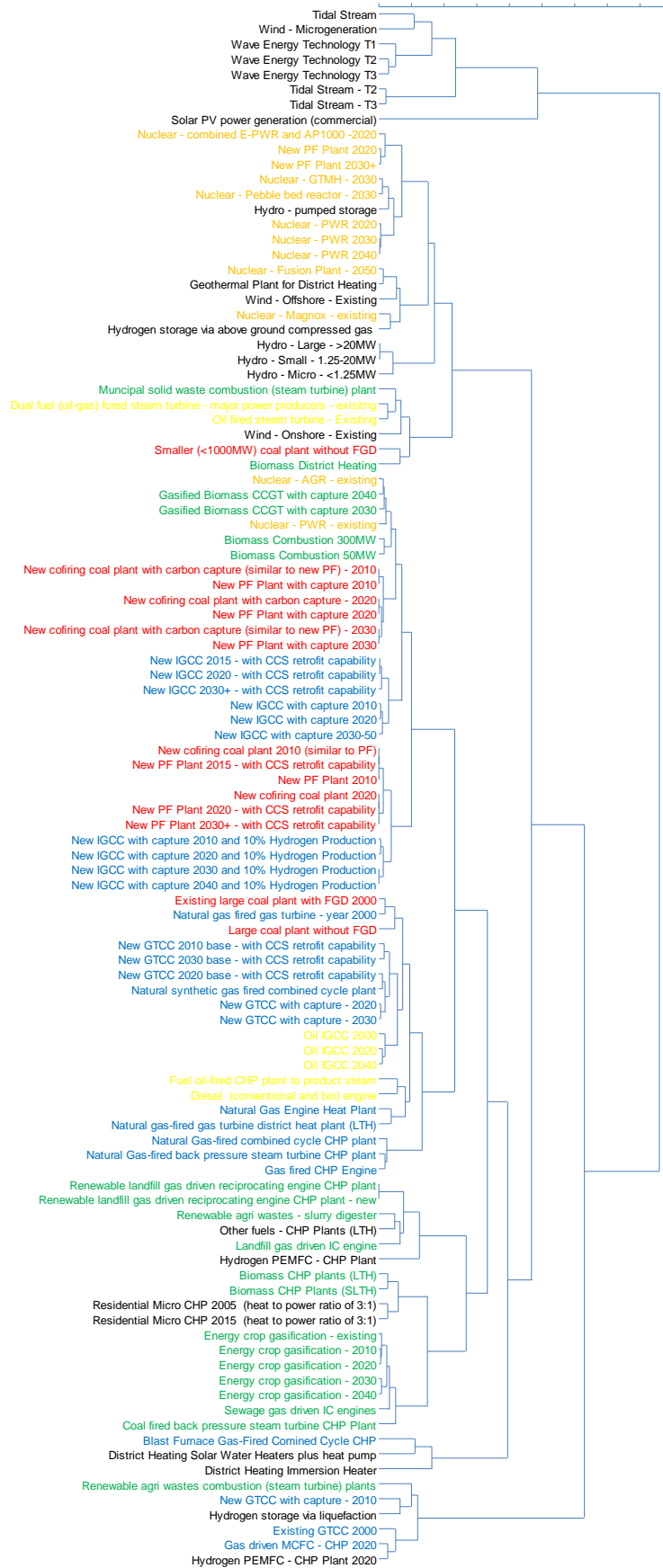
APPENDIX 1 – Interviewee Dendrograms



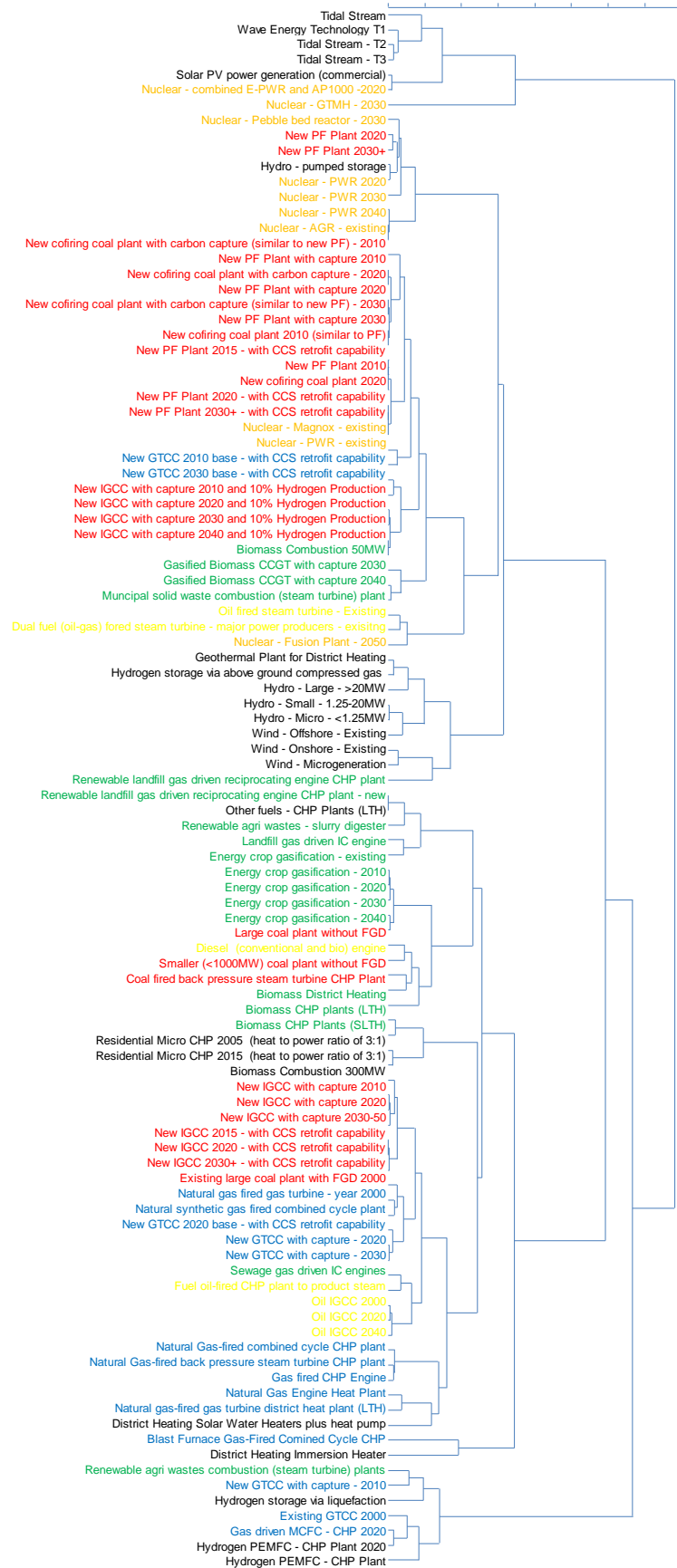
SPA2



SPA3



SPA4



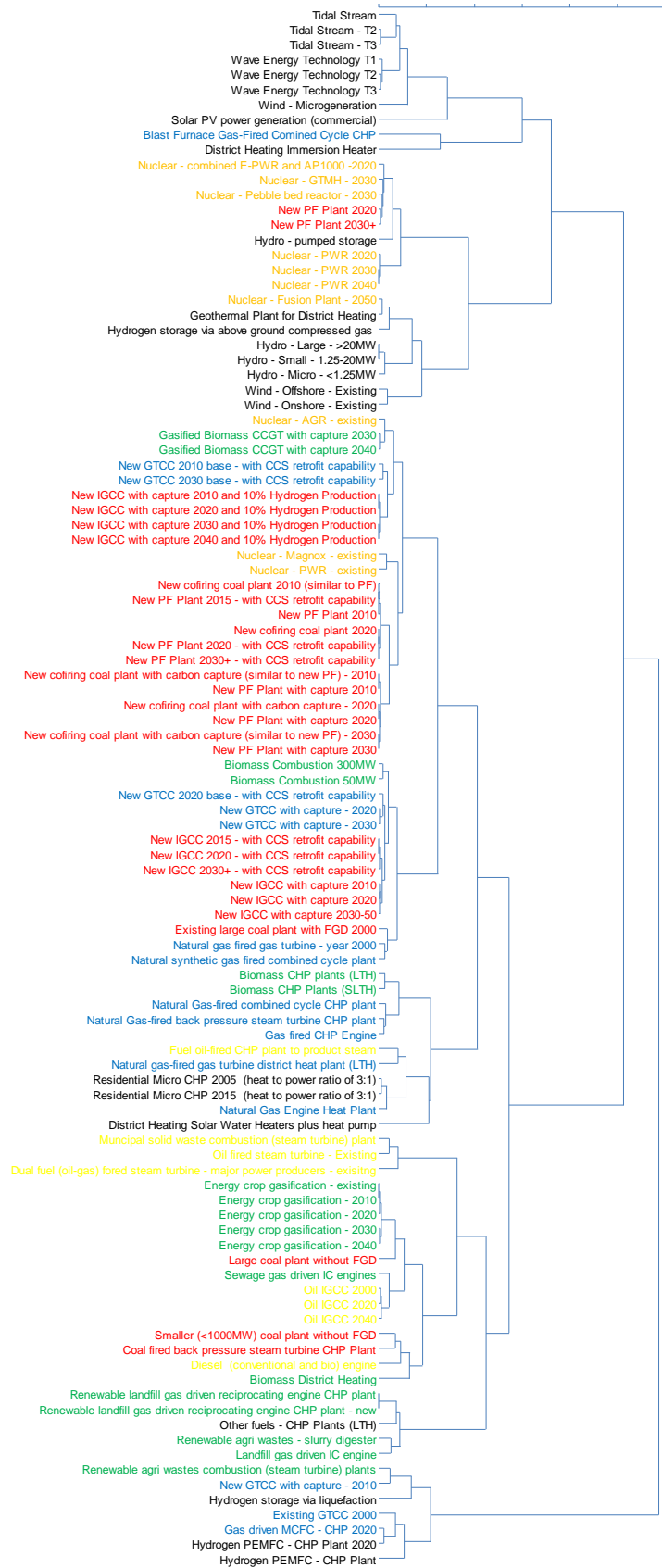
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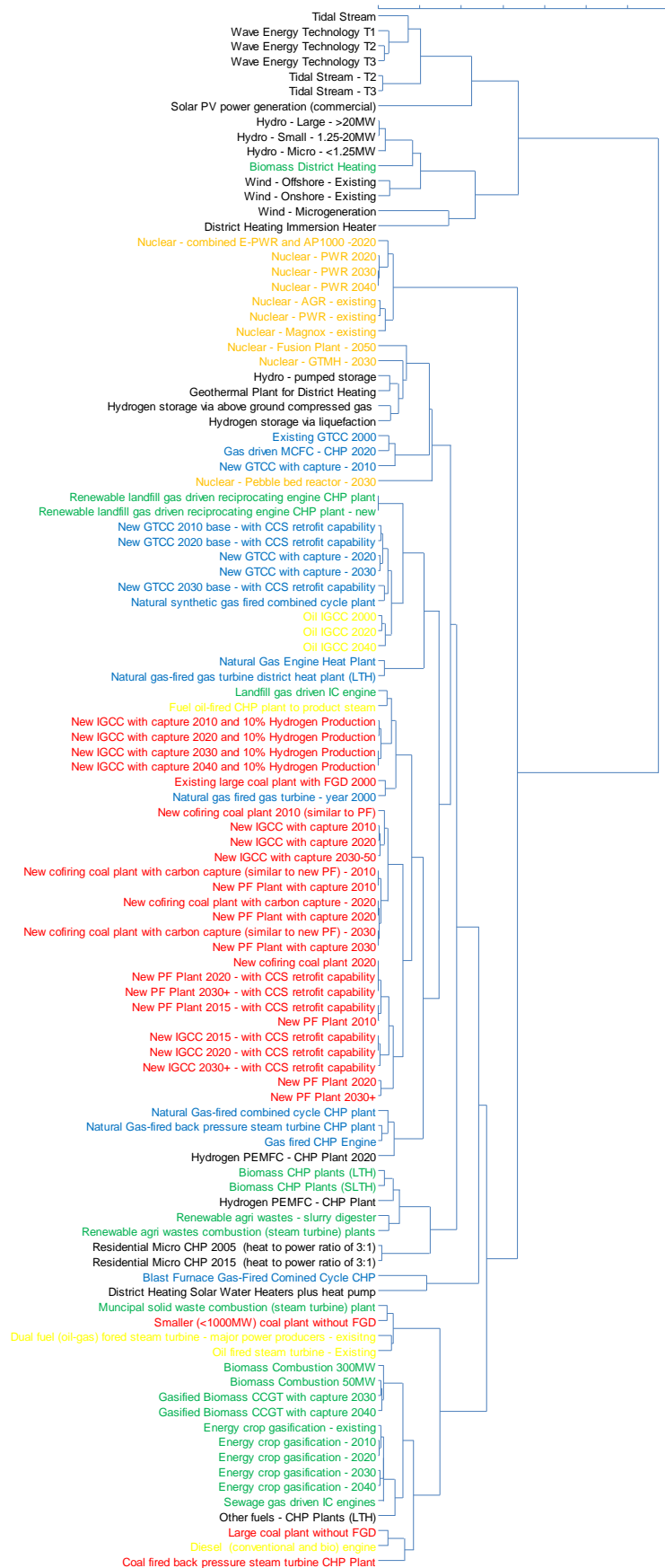
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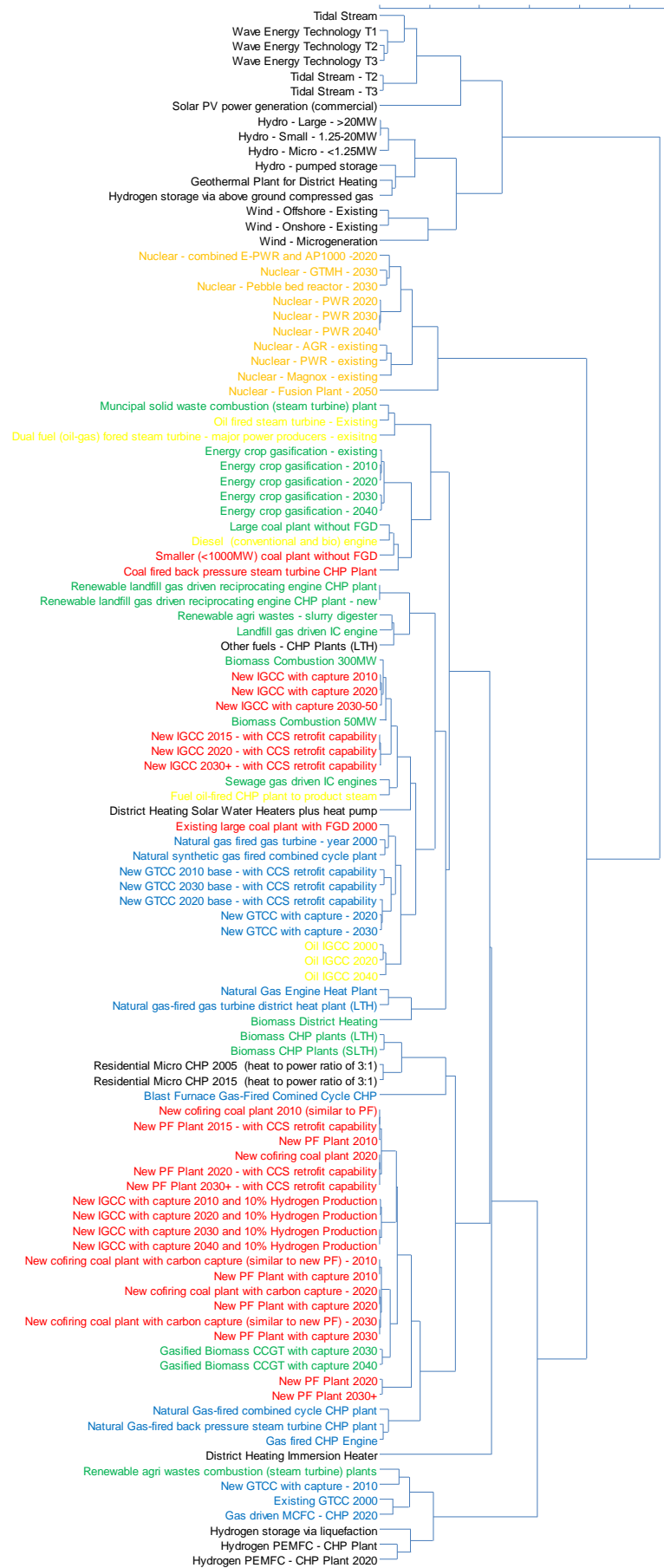
SPA8



SPA10

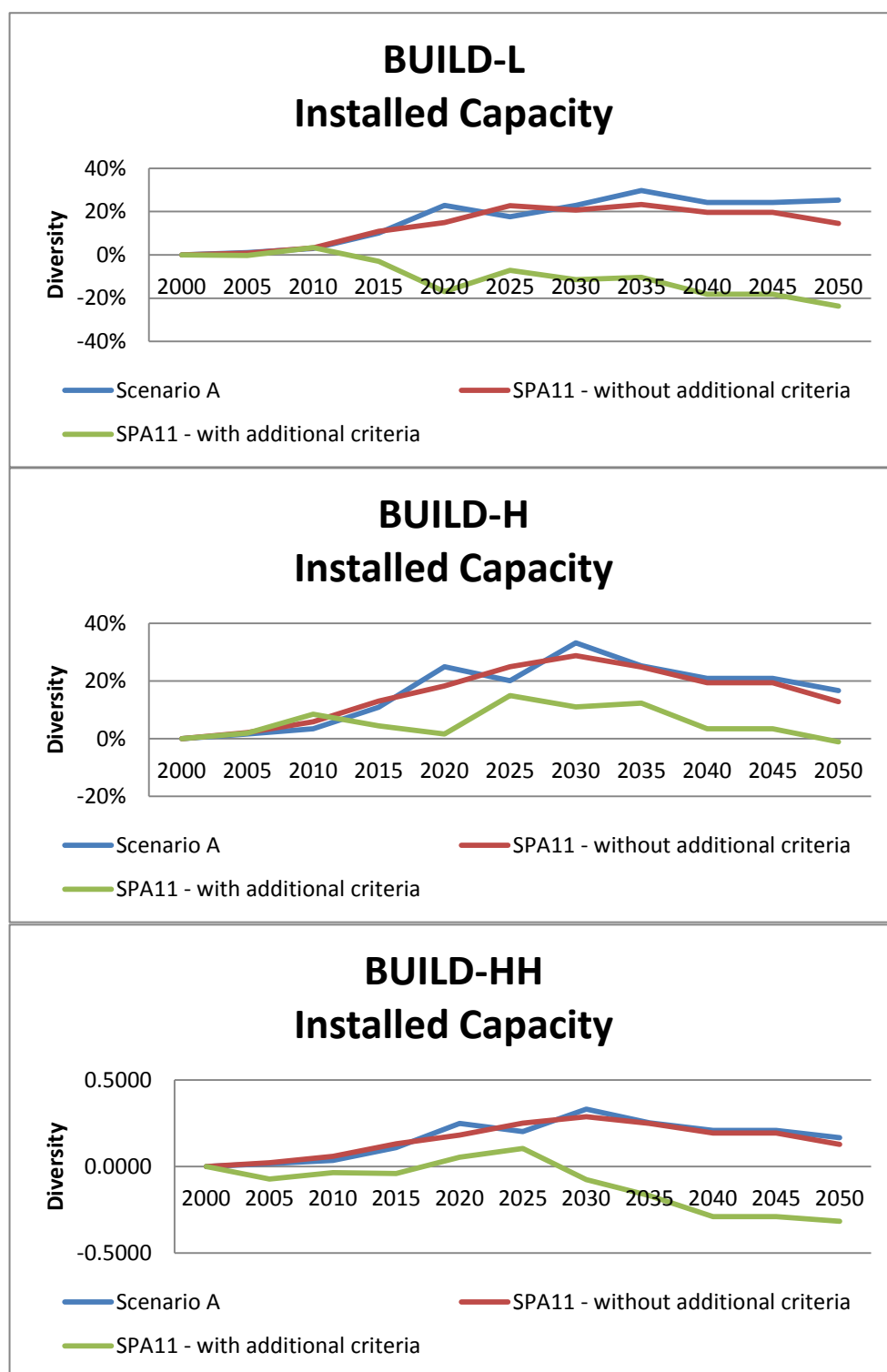


SPA12



APPENDIX 2 – Diversity Profiles for Additional Criteria

Diversity profiles with and without additional criteria for interviewee SPA11 for the CCS build rate scenarios



Diversity profiles with and without additional criteria for interviewee SPA11 for the CCS capital cost scenarios

